AN ABSTRACT OF A THESIS

AN ASSESSMENT OF WOOD DUCK BANDING NEEDS OF THE MISSISSIPPI AND ATLANTIC FLYWAYS

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The successful management of game species requires sustainable harvest strategies that meet the needs of the present and future. Paramount to developing such strategies is the effective monitoring of population trends and demographic rates. Wood ducks (*Aix sponsa*) are one of the most important game species in the Mississippi and Atlantic Flyways, consistently being among the most harvested waterfowl species in each respective Flyway. Due to the species extensive breeding range and use of forested wetlands, monitoring wood duck population size and demographic rates is a challenge for waterfowl managers. Currently, harvest estimates derived from banding data are directly used to inform annual harvest management decisions in the Mississippi and Atlantic Flyways; however, banding quotas in these Flyways have not been updated in more than 20 years. During this time, there have been increases in band reporting rates in addition to substantial shifts in banding distributions that could bias estimates and hinder effective management decisions. Therefore, I evaluated demographic rates using capture-mark-recovery data of pre-season banded wood ducks from 2000–2022 to provide the Mississippi and Atlantic Flyways with updated banding goals. I fit a dead-recovery model with Brownie parameterization within a Bayesian framework at varying spatial scales to identify patterns in spatial variation of demographic rates. I found demographic rates varied along latitudinal gradients and identified three subpopulation regions in eastern North America. Categorizing data within these three regions maximize harvest rate variation between each region while minimizing variation within each region. Using my estimates of harvest and natural mortality, I then simulated various banding efforts at these scales to understand how shifts in banding distributions affect harvest rate estimates and precision at the Flyway level. I found at the current flyway management scale precision targets are being met for all cohorts except adult females in the Atlantic Flyway. However, I provide evidence to support shifting to management regimes that are latitudinally stratified. At my identified Three Latitudinal Regions scale, banding would need to increase in southern portions of both Flyways to reach desired precision for adult females. The establishment of these regions that encompass both flyways allow for the prescription of attainable banding goals at a more biologically relevant scale. With increasing constraints on federal and state agencies to implement banding programs, our newly defined regions will increase the efficient and practical application of preseason wood duck banding while increasing robustness of Flyway-level estimates to changing band deployment distributions over time.

AN ASSESSMENT OF WOOD DUCK BANDING NEEDS OF THE MISSISSIPPI AND ATLANTIC FLYWAYS

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TABLE OF CONTENTS

Pages

LIST OF TABLES ix
LIST OF FIGURES xi
CHAPTER ONE: INTRODUCTION AND LITERATURE REVIEW 1
INTRODUCTION 1
LITERATURE REVIEW 4
Continental Waterfowl Management 4
Waterfowl Banding 5
Wood Ducks 7
Wood Duck Management 9
Objectives 12
LITERATURE CITED 13
CHAPTER TWO: AN ASSESSMENT OF WOOD DUCK BANDING NEEDS OF THE MISSISSIPPI AND ATLANTIC FLYWAYS 23
Abstract 24
INTRODUCTION 24
STUDY AREA 27
METHODS 27
Band-recovery data 27
Mark-recovery model 29
Spatial variation in harvest rates 31
Simulations 32
Computations 34
RESULTS 34
Spatial variation in harvest rates 34
Simulations 36
DISCUSSION 39
MANAGEMENT IMPLICAITONS 42
ACKNOWLEDGMENTS 42
LITERATURE CITED 43

APPENDICES 78
Appendix A. Figures 78
Appendix B. Tables 90
CHAPTER THREE: SUMMARY AND CONCLUSIONS 95

LIST OF TABLES

Table 1. The States and Provinces of eastern North America divided by administrative Flyway and wood duck banding reference areas from Kelley (1997).. 54

Table 2. Regional divisions created to asses demographic rate variability of preseason banded wood ducks in eastern North America from 2000–2022. These regions include Mississippi and Atlantic Flyways, the number of strata (*k*) created in each sub-division, and each sub-division coefficient of variation (CV) rank according to our harvest CV ratio. This ratio was calculated by dividing the coefficient of variation among by the coefficient of variation within the spatial strata and each sub-division was ranked from best (greatest variation ratio) to worst (smallest variation ratio)................................... 55

Table 3. Banding distribution simulation scenarios created to evaluate shifts in preseason wood duck banding distributions in eastern North America (Mississippi and Atlantic Flyways combined) including the geographic scale, simulation name, and description. 57

Table 4. The average banding distribution, frequency, and percentage of preseason banded wood ducks in our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway from 2016–2021. Banding frequencies are divided by Latitudinal Regions (North, Central, South) within each geographic scale determined using demographic rate variability.. 60

Table 5. The average percentage of each wood duck cohort banded in our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway from 2016–2021. Banding frequencies are divided by latitudinal regions (North, Central, South) within each geographic scale determined using demographic rate variability. 61

Table 6. The estimated average harvest rate and standard deviation (SD) from 2000–2022 of preseason banded wood in our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway. Harvest rate and standard deviations are divided by latitudinal regions (North, Central, South) within each geographic scale determined using demographic rate variability. 62

Table 7. The estimated average natural mortality rate and standard deviation (SD) from 2000–2022 preseason banded wood in our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway. Natural mortality rates and standard deviations are divided by latitudinal regions (North, Central, South) within each geographic scale determined using demographic rate variability. 63

Table 8. Average estimated survival rates and coefficient of variation (CV) of preseason banded wood ducks wood ducks from 2000-2022 in eastern North America estimated for each Kelley (1997) region and Flyway. 64

Table 9. Average estimated harvest rates and coefficient of variation (CV) of preseason banded wood ducks wood ducks from 2000-2022 in eastern North America, estimated for each Kelley (1997) region and Flyway. 65

Table 10. Banding recommendations to meet the ≤7% five-year mean coefficient of variation target for preseason banded Adult female and male wood ducks for our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway. Recommendations provided are a total number of deployments given the current percentage each cohort makes of band deployments. 66

LIST OF FIGURES

Figure 1. We derived wood duck demographic rates from 2000–2022 from banding data in a mark-recovery framework at varying spatial scales to identify possible new wood duck management regions. We divided eastern North America into various strata to compare demographic rates of wood ducks banded in each. We found that equal break, three latitudinal bins (a) division maximized demographic rate variation between each stratum while minimizing variation within each stratum. From this we created a three latitudinal regions (b) division, dividing states and provinces along those latitudinal lines. We then also divided these regions by Flyway (c) to create six different regions for Flyway administrative purposes. 67

Figure 2. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Atlantic Flyway Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male). Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance.. 68

Figure 3. Bias of harvest rate estimates for each Atlantic Flyway Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male). Bias was derived by simulated each banding scenario 100 times for a

five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data. 69

Figure 4. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Mississippi Flyway Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male). Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance. 70

Figure 5. Bias of harvest rate estimates for each Mississippi Flyway Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male). Bias was derived by simulated each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization

(Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data............ 71

Figure 6. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each of our identified regions. Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance. 72

Figure 7. Bias of harvest rate estimates for each Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each region. Bias was derived by simulated each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data............ 73

Figure 8. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Mississippi Flyway Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each of our identified regions. Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance.. 74

Figure 9. Bias of harvest rate estimates for each Mississippi Flyway Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each region. Bias was derived by simulated each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data.. 75

Figure 10. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Atlantic Flyway Three Latitudinal Region Simulation scenario of each preseason

banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each of our identified regions. Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance. 76

Figure 11. Bias of harvest rate estimates for each Atlantic Flyway Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each region. Bias was derived by simulated each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data.. 77

CHAPTER ONE: INTRODUCTION AND LITERATURE REVIEW

INTRODUCTION

The North American Model of Wildlife Management (NAMWM) has emerged as the most successful and enduring conservation model globally. First adopted by the United States, Canada, and eventually Mexico, the model is rooted in seven key principles, termed the "seven sisters of conservation" (Organ et al. 2012). These tenants now form the back bone of wildlife conservation policy and practice across federal, state, and private organizations. One fundamental NAMWM principle is the Roosevelt Doctrine, which recognizes science as the proper tool to guide wildlife management decisions and policymaking. This doctrine affirms the importance of grounding conservation in evidence-based decision making, ideally isolated from political influences (Organ et al. 2012). However, emerging issues like climate change, urbanization, and novel diseases create management uncertainties not envisioned by NAMWM architects. Moreover, traditional funding sources for conservation science are declining, while political interference in agency decision-making threatens the Roosevelt Doctrine. Ensuring the relevancy of the NAMWM in modern contexts requires elucidating pathways to uphold scientific integrity. Adaptively integrating new monitoring technologies, analytical tools, and collaborative conservation approaches could strengthen scientific foundations supporting proactive wildlife management.

The NAMWM was constructed by sportsmen with a conservation or "wise use" ethic in mind and is the basis for sustainable consumptive use of game species through proper management. The goal of sustainable use is to meet the needs of the present and future generations accounting for the interdependence of economic activity and ecological status

(Wefering et al. 2000). For any given game species, there is a range of harvest rates that will allow for biologically self-sustaining populations over time (Rosenberg et al. 1993). However, natural resource agencies managing game species consistently depend on imperfect methods for monitoring, assessment, and enforcement. This uncertainty in addition to the stochasticity of natural systems makes implementing sustainable harvest a complex challenge (Irwin and Conroy 2013). To reduce this uncertainty, wildlife agencies invest substantial resources into the monitoring of wildlife populations (Witmer 2005).

Monitoring wildlife populations involves the assessment of the status, density, or vital rates of a population within a defined area over a period of time (Thompson et al. 1998, Bolen 2000). There are variety of traits that can be monitored, and although abundance is the most common, vital rates such as fecundity, survival rate, death rate, and harvest rates are extremely informative to help identify changes in populations and the severity of changes (Thompson et al. 1998). Researchers have developed a variety of monitoring methods, each with certain strengths and weaknesses (Seber 1973, Thompson et al. 1998, Schwarz and Seber 1999). Population monitoring can be divided into categories of index and inferential monitoring (Thompson et al. 1998). Although index monitoring is coarser and can only provide broad inferences, it is typically less expensive and can include collecting nonrandom samples or descriptive data. Inferential monitoring typically uses unbiased protocols, and is more informative as it can be expanded to an entire area of interest; however inferential monitoring programs typically come with a higher cost and labor requirement (Thompson et al 1998).

One of the most widely used population monitoring methods is the mark-recapture method, with an estimator originally developed by Lincoln (1930). This method involves capturing animals in the population of interest, marking them with an identifier, and releasing them back into the environment to mix with the greater population. Then, by ether capturing animals again or identifying marked individuals, a population estimate can be obtained using a ratio of marked and unmarked individuals. Since the development of the original estimator, there have been a variety of different statistical models developed from this basic sampling design with a variety of assumptions about the population of interest (Pollock 2000). Mark-recapture models can be used to estimate not only abundance but also vital rates including survival and harvest rates of game species populations. Together estimates of survival and harvest from mark-recapture models can be used to understand population growth rates in a harvest framework that ensures suitability (Runge et al. 2009). Given the importance of population monitoring, especially for sustainable management of game species, mark-recapture methods are an invaluable tool to wildlife managers.

Wood ducks (*Aix sponsa*) are one of the most harvested waterfowl species in the Mississippi and Atlantic Flyways (Fronczak 2021, Raftovich et al. 2022). However, due to their extensive breeding range and use of forested wetlands, traditional aerial monitoring methodology is ineffective (Garretson 2007, Zimmerman et al. 2015, Garrettson 2021). Given this constraint, use of mark-recovery data from pre-season (July–September) wood duck banding is the most efficient and effective method for monitoring populations and demographic rates (Kelley 1997, Garrettson 2007, Garrettson 2021). Wood duck banding quotas in eastern North America have not been updated in more than 20 years. There have been major shifts in band deployment distribution and an increase in band reporting rates (Boomer et al. 2013, Garrettson et al. 2014, Arnold et al. 2020). With an increase in reporting rates, fewer bands are likely needed for precise demographic estimates required for management decisions (Garrettson 2021). In addition, shifts in band deployment distributions could bias estimates of demographic rates needed to implement sustainable harvest strategies, thus leading to improper management (Greenawalt et al. 2022). Given these changes, managers need to understand how banding distributions and quantities affect estimates and the precision of those estimates to implement sound harvest strategies.

LITERATURE REVIEW

Continental Waterfowl Management

Sparked by declining waterfowl populations in the mid-1900s, a comprehensive continent-wide management plan known as the North American Waterfowl Management Plan (NAWMP; U.S. Department of the Interior, and Environment Canada 1986) was enacted. A key factor leading to NAWMP's success was the ability to step-down continent-wide goals into regional actionable steps through Joint Ventures (JVs). Joint Ventures were established as public and private partnerships to fund and implement high-priority research and habitat projects (U.S. Department of the Interior, and Environment Canada 1986). Today there are 22 regional habitat JVs that span most of the continent, and three species specific JVs (National Joint Venture Communications, Education, and Outreach Team 2020). Although many of these regional JVs advocate for all migratory birds, waterfowl habitat remains the central focus of several due to funds, support, and infrastructure (Anderson et al. 2018). A major part of NAWMP's success has been its evolution through revision; the plan was most recently revised in 2012 and updated in 2018. The revisions of NAWMP have included new objectives while addressing previous accomplishments and future challenges (U.S. Department of the Interior, Environment Canada, and Environment and Natural Resources Mexico. 2018).

In 1995, the U.S. Fish and Wildlife Service (USFWS) introduced the adaptive harvest management (AHM) program for setting duck harvest regulations in the U.S. (Blohm 1989, Nichols et al. 1995, Williams and Johnson 1995). The program was introduced to make objective management decisions with incomplete knowledge of waterfowl population dynamics (Williams and Johnson 1995, USFWS 2022). AHM relies on a constant cycle of monitoring, assessment, and decision making to identify the interactions among regulations, harvest, and waterfowl abundance (Johnson et al. 2015). Under the AHM program, hunting regulations are set annually, which involves choosing the best regulatory option given the resource, environmental conditions, and population models (Blohm 1989, USFWS 2022). Once a regulatory option is chosen, model performance is evaluated and weighted using monitoring data. The process of updating model weights aims to ultimately find the best model at predicting population abundance (Nichols et al. 2007, USFWS 2022). At this time, three stocks (distinct populations) of waterfowl are used in the AHM process. The Pacific Flyway regulatory strategy is based on the status of the western-mallard stock. The Central and Mississippi Flyways strategies are based on the mid-continent mallard stock (USFWS 2022). The Atlantic Flyway differs, with its regulatory strategy being based on the multi-stock model. The multi-stock model considers the status of four species, American green-winged teal (*Anas carolinensis*), wood ducks (*Aix sponsa*), ring-necked ducks (*Aythya collaris*), and goldeneyes (both *Bucephala clangula* and *B. islandica* combined) breeding in the Flyway (Roberts et al. 2022, USFWS 2022).

Waterfowl Banding

The practice of marking the legs of avian species dates back to 1804 when John James Audubon tied threads to the legs of songbirds to see if individuals returned to the same location annually (Rydzewski 1951, Bolen 2000). In North America, serial numbered bands were first used on herons in 1902 (Bartsch 1952). The banding of waterfowl was at first a completely private practice; in 1909 the American Ornithologist Union created the Bird Banding Association to combine the efforts of private banders. The association was then later coordinated by Fredrick Lincoln of the Bureau of Biological Survey which led to fundamental discoveries in waterfowl management. Using banding data, Lincoln (1935) first described the four major migratory routes coined “Flyways” that waterfowl in North America travel. The four Flyways are still used today: Atlantic, Mississippi, Central, and Pacific (Lincoln 1935). This information would be used to form the Flyway Councils in 1948. These councils serve as units for policy making regarding waterfowl management in each Flyway; the councils are informed by technical committees that provide a scientific foundation for management action through harvest assessments and research (Bolen 2000). The efforts of Lincoln would later go on to produce the Bird Banding Laboratory (BBL) that oversees all bird banding in the United States and works in conjunction with the Canadian Bird Banding Office (BBO; Buckley et al. 1998).

Waterfowl banding provides key data to estimate harvest, survival, abundance, and movement patterns of a variety of species (Alisauskas et al. 2009, Alisauskas et al. 2011, Sedinger et al. 2019). Species and age specific demographic rates estimated from banding data are directly used in the regulatory process to set and open waterfowl seasons annually (Williams and Johnson 1995, Pollock and Raveling 1982, USFWS 2022). Although waterfowl banding has been implemented for over 100 years with several foundational methods to analyze banding data (i.e., Lincoln (1930) estimator, Seber (1982) CJS models, and Brownie et al. (1985) models), newer statistical approaches are now being applied using these foundational concepts. Specifically, Bayesian approaches are implemented to estimate waterfowl population size and demographic rates (Sedinger et al. 2019, Thompson et al. 2021, Greenawalt 2023). Bayesian methods offer several advantages including the use of informative prior probability distributions and the characterization of uncertainty in parameter estimates (McCaffery et al. 2012, Maunder and Punt 2013, Hobbs and Hooten 2015). Bayesian methods allow for the transfer of information regarding uncertainty from one analysis to another, or the use of expert opinion in the form of informative prior distributions to model parameters (Kéry and Schaub 2012, Maunder and Punt 2013).

The analysis of waterfowl banding data makes several assumptions regarding the distribution of banded birds in the population, fates of banded birds, and models themselves (Brownie et al. 1985). The first assumption is that the sample (birds banded) is representative of the population (Brownie et al 1985, Williams et al. 2002, Alisauskas et al. 2009). This assumption could easily be violated if different segments of the population use different staging areas, meaning the banded sample potentially could not be appropriately distributed across the landscape (Pollock and Raveling 1982, Royle and Dubovsky 2001, Greenawalt et al. 2022). In addition, birds banded at different times at staging areas could migrate in different segments affecting survival rate (Pollock and Raveling 1982). It is key that banded birds have the same harvest probabilities as unbanded birds (Alisauskas et al. 2009). Another fundamental assumption of many band-recovery models is that individuals in the same identifiable class (e.g. age or sex) have the same annual survival and recovery rates (Brownie et al. 1985). This assumption can also be violated given migrations often encompass multiple Flyways or wintering sites. In addition, hunting pressure can vary by state and region due to habitat variability (Pollock and Raveling 1982). Given the assumptions of band-recovery models, it is essential that geographic and cohort distributions of banded birds are carefully considered to obtain accurate estimates (Brownie 1985).

Wood Ducks

Wood ducks are a common and widespread species in North America, and one of the most harvested duck species in the Atlantic and Mississippi Flyways (Fronczak 2021, Raftovich et al. 2022). Wood ducks are able to utilize a variety of wetland types and vegetation communities, which contributes to their large distribution in North America (Bellrose and Holm 1994, Davis et al. 2007, Dyson et al. 2017). Their habitat use and dietary requirements vary seasonally. During winter the vast majority of wood ducks' diet is made up of plant foods including seed and a large portion of acorns (Delnicki and Reinecke 1986, Dugger and Fredrickson 1992). The females will prioritize seeds to increase lipid reserves pre-laying and then switch to invertebrates that provide female wood ducks the protein required during the egg-laying process (Drobney and Fredrickson 1979, Drobney 1982). Wood ducks primarily feed on or near the surface of the water while swimming and will less frequently travel on dry land to feed (Dugger and Fredricson 1992, Bellrose and Holm 1994). While wood ducks will feed sub-surface they rarely "tip-up" like many other species and actually feed more by pecking (Bellrose and Holm 1994). Due to their feeding habits, wood ducks feed mostly in shallow water and on the edge of wetlands; however, when resources are depleted they will travel to upland sites and cereal grain fields to find food (Bellrose and Holm 1994, Davis et al. 2007, Dyson et al. 2018).

Wood ducks are a secondary cavity-nesting species and were thought to be limited by the quantity of available cavities on the landscape (Bellrose et al 1964, Bellrose and Holm 1994, Davis et al. 2007). For a wood duck to nest in a natural cavity it must meet certain requirements such as having the right entrance size (≈11 by 20 cm), be high enough off the ground (≈ 7.6 meters), have the right cavity volume (≈ 20,000 cm^3), and be located close enough to adjacent wetlands (< 1.6km; Bellrose et al. 1964, Gilmer et al. 1978, Robb 1986, Bellrose and Holm 1994). Natural cavities of this kind are also highly sought after by a variety of species including other cavity-nesting waterfowl, fox squirrels, racoons, and opossum, which further reduces the number of suitable cavities (Bellrose and Holm 1994, Robb and Bookhout, 1995, Bakner et al. 2022). This niche that wood ducks fill highlights its dependency on wooded wetlands and woodlands adjacent to wetlands, accentuating how forest clearing along with wetland degradation have been and still are particularly harmful to the species.

The wood duck is one of the very few North American waterfowl species with large migratory and nonmigratory portions of its greater population (Hepp and Hines 1991, Bellrose and Holm 1994). In eastern North America, wood ducks that breed south of North Carolina, Tennessee, and Little Rock, Arkansas are essentially nonmigratory. Approximately 40% of wood ducks in the Atlantic Flyway and 30% of wood ducks in the Mississippi Flyway are nonmigratory (Bellrose and Holm 1994). Conversely, wood ducks that breed in the northern latitudes travel greater distances, which has been shown to lead to a lower survival rate (Heusmann and McDonald 2002, Garrettson 2007). Nichols and Johnson (1990) attributed this lower survival rate to reduced fitness from migration cost. For the wood ducks that do migrate long distances latitudinally, autumn migration is also earlier than most other waterfowl species. Migration is initiated in September with almost all birds departed from northern latitude states by mid-November (Bellrose and Holm 1994, Greenawalt 2023). Due to this migration inconstancy, wood ducks breeding in northern latitudes also experience higher rates of harvest (Nichols and Johnson 1990, Bellrose and Holm 1994, Heusmann and McDonald 2002). Heusmann and McDonald (2002) highlight that current regulations benefit southern wood duck hunters over their northern counterparts as wood ducks are only available to harvest for a short period of the hunting season in some portions of their northern range.

Wood Duck Management

Typical for most waterfowl species, separate wood duck harvest management strategies were developed by the Atlantic and Mississippi Flyway Councils (Heusmann and Sauer 2000, Chasko and Brakhage 1990, Mississippi Flyway Council 1994). In 1993, a joint strategy was developed between both Flyway councils and the USFWS. The purpose of the initiative was to delineate subpopulations, improve banding programs, assess methods for monitoring the size of breeding subpopulations, and evaluate methods of measuring productivity (Kelley 1997). However, this proved no simple task, and Kelley (1997) described the development of population monitoring programs for wood ducks as one of the most challenging tasks facing waterfowl managers at that time. Due to their broad geographic breeding range, population complexity, and use of forested wetlands, traditional aerial survey methods during spring are ineffective (Kelley 1997, Garrettson 2007, Zimmerman et al. 2017). Given the complexity of wood duck populations, attempts were made to define subpopulations (Bowers and Martin 1975, Kelley 1997). Broken down at first at the Flyway level and then aggregated by states, Bowers and Martin (1975) first defined six wood duck subpopulations in the Mississippi and Atlantic Flyways based on band-recovery data that then served as banding reference areas (Johnson et al. 1986, Nichols and Johnson 1990, Sauer et al. 1990, Trost 1990). These six were then updated by Kelley (1997), and subpopulation regions in the Mississippi Flyway remained the same while the Atlantic had a slight change.

Kelley (1997) examined several potential methods for monitoring wood ducks. Of the available options, he found aggregating existing North American Breed Bird Survey (BBS) routes and band recovery data to be the most useful. With this information, a ground-based plot survey called the Atlantic Flyway Breeding Waterfowl Survey (AFBWS) was started in 1993 to provide estimates of wood duck population abundance covering the northeastern U.S. states from

New Hampshire to Virginia (Heusmann and Sauer 2000). This survey, in combination with BBS data, provides abundance estimates for the entire Atlantic Flyway (Zimmerman et al. 2015, 2017). However, these surveys have limitations. BBS estimates are not adequate for annual management decisions due to low detection probabilities because the survey was not originally intended for wood ducks (Zimmerman et al. 2015). Combining data from the AFBWS and BBS made significant progress for monitoring wood ducks in the Atlantic Flyway, no such surveys currently exist in the Mississippi Flyway.

The utility of wood duck banding and recovery data has been shown for both population and harvest estimates (Kelley 1997, Garrettson 2007, Garrettson 2021, Greenawalt et al. 2022, Greenawalt 2023). However, this utility comes with several major caveats. First the banded sample must be representative of the population as a whole (Brownie et al. 1985, Alinsuks et al. 2009). Ensuring a proper distribution of banded birds is particularly challenging given the vast breeding range of wood ducks (Kelley 1997, Greenawalt et al. 2022). In addition, the variance associated with estimated vital rates depends upon the quantity of both banding and recoveries (Garrettson 2021). Garrettson (2021) also showed that the vital rates among the Kelley (1997) regions not only differed but also that most of these regions would need to increase banded sample by 2–to–10–fold in order to meet harvest estimate precision levels of just 15% coefficient of variation (CV). Currently, the Mississippi Flyway has been engaged in the double-looping process and the Atlantic Flyway has moved to a multi-stock management, but the need for robust banding program continues; the species is among the most harvested in both Flyways and there is still no range-wide population survey (Zimmerman et al. 2017, Raftovich et al. 2022, USFWS 2022). Banding and wood duck committees in both Flyway technical sections have shown interest in calculating updated banding goals based on the methods of Kelley (1997) that would provide guidance in maintaining a sound banding program to meet management needs (Garrettson 2021). Most recently, research conducted by Greenawalt et al. (2022) identified several keys to establishing effective wood duck banding goals. First, there is substantial variability in harvest rate estimates at some spatial scales. Second, the recent decline in wood duck band deployments, generally in the southeast will decrease the precision of demographic rate estimates. This imbalance in banding effort among states could bias harvest rates and lead to erroneous harvest management decisions. Given the use of wood duck banding data to inform annual waterfowl seasons and bag limits, the establishment of updated wood duck banding goals for the Mississippi and Atlantic Flyways is critical for effective wood duck management in eastern North America (Garrettson 2007, Garrettson 2021, USFWS 2022).

Objectives

Understanding how the spatial distribution and quantity of marked individuals affects estimates from mark-recovery analysis is critical. Wood ducks are a cryptic species with no superior monitoring method to band-recovery data. Given the importance of wood duck banding data in the annual management cycle, I examined various spatial scales and features to assign appropriate and attainable banding goals given varying vital rates and habitat features throughout the Mississippi and Atlantic Flyways. My specific objectives were to:

1. Identify the spatial scale at which demographic rates (i.e., survival, hunting mortality, and natural morality) vary substantially to potentially affect harvest management decisions.
2. Simulate varying banding efforts at the identified spatial scale to forecast how banding distributions will affect demographic rate estimates.

3. Provide Wood Duck banding goals for the Mississippi and Atlantic Flyways that will provide single year harvest estimates to meet their desired precision threshold of a CV at or under 15% and a 5-year mean estimates with a CV ≤7%.

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CHAPTER TWO: AN ASSESSMENT OF WOOD DUCK BANDING NEEDS OF THE MISSISSIPPI AND ATLANTIC FLYWAYS

[1]Howard, C. A., A. C. Keever, A. C. Greenawalt, P. M. Garrettson, H. M. Hagy, and B. S. Cohen. 2023. An assessment of wood duck banding needs of the Mississippi and Atlantic Flyways. To be submitted to Journal of Wildlife Management.

Abstract Sustainable game management requires effective monitoring of population trends and demography. As a heavily harvested species with cryptic forested wetland habitat, monitoring wood duck (*Aix sponsa*) abundance and vital rates has challenged managers. We used capture-mark-recovery data of preseason banded wood ducks from 2000-2022 to evaluate spatial variation in banding data-derived demographic rates and provide updated monitoring recommendations. We fit a dead-recovery model with Brownie parameterization within a Bayesian framework at varying spatial scales to identify where demographic rates most varied. Bayesian survival analysis revealed latitudinal gradients in wood duck demography within the Atlantic and Mississippi Flyways. We identified three regions maximizing inter-region variation and minimizing intra-region variation of wood duck demographic rates. We then simulated variation in regional banding effort and distribution to explore effects on precision at varying management scales and found low banding numbers in some areas of the Atlantic Flyway jeopardize inference quality. Our approach illustrates the importance of periodically reevaluating monitoring frameworks as population dynamics, management contexts, and analytical techniques evolve. Although current banding distribution and analysis at the Flyway scale are largely meeting precision goals, the different annual demographic and harvest rates of wood ducks among breeding latitudes are not currently accounted for and changes in band distribution inequitably across these regions will directly influence demographic rates. We recommend revised banding goals and annual estimation by latitudinal region to optimize wood duck harvest management and account for changes in band distribution over time.

KEY WORDS wood duck, waterfowl management, Atlantic Flyway, Mississippi Flyway, mark-recovery.

INTRODUCTION

Sustainable harvest strategies balance present use and future conservation (Wefering et al. 2000, Heffelfinger et al. 2013). Although reliable population monitoring data enables informed harvest management decisions (Witmer 2005, Runge et al. 2009, USFWS 2022), they are challenging to obtain given the required cost, equipment, and staffing (Thompson et al 1998). For waterfowl, aerial surveys and banding data are used to effectively track populations for many species in North America (Nichols et al. 2007, USFWS 2022). However, for some waterfowl species like wood ducks (*Aix sponsa*) with large geographic breeding ranges and low detection probabilities, aerial surveys are not feasible and banding adequate numbers is challenging (Kelley 1997, Garrettson 2007).

Wood ducks hold the peculiar distinction of being one of the most heavily harvested, yet cryptic, waterfowl species in eastern North America (Fronczak 2021, Raftovich et al. 2022). Breeding across a broad geographic range primarily from Canada to the Gulf Coast east of the Mississippi River in North America, wood ducks inhabit forested wetlands that precludes traditional aerial survey techniques (Bellrose et al. 1964, Bellrose and Holm 1994, Davis et al. 2007). Similarly, ground based surveys are limited geographically and have low detection probabilities (Zimmerman et al. 2015, 2017). Subsequently, banding data have become the primary source of population monitoring for this species (Kelley 1997, Garrettson 2023). However, the utility of banding hinges on key assumptions, including representative sampling and equal survival and recovery rates between distinct subpopulations and migration strategies (Brownie et al. 1985, Alisauskas et al. 2009). Given the species' extensive range and migratory polymorphism (Hepp and Hines 1991, Bellrose and Holm 1994), verifying these assumptions remains challenging but critical for unbiased estimation (Pollock and Raveling 1982, Nichols and Johnson 1990).

Research indicates substantial spatial variability in wood duck vital rates, such as differential harvest exposure between northern and southern breeding populations (Heusmann and McDonald 2002, Greenawalt et al. 2022). Specifically, wood ducks banded in more northern latitudes travel further distances and have greater harvest and lower survival rates (Nichols and Johnson 1990, Bellrose and Holm 1994, Heusmann and McDonald 2002, Garrettson 2007). The heterogeneity in vital rates may result in biased inferences if sampling and banding effort fail to adequately capture this diversity or do so variably over time and space (Pollock and Raveling 1982, Brownie 1985). Banding goals have not been reevaluated in over 20 years, despite changes in reporting rates, regulations, and available analytical techniques (Kelley 1997, Garrettson and Howard 2023). Updated benchmarks tailored to the species' regional demography are needed to optimize monitoring.

Wood duck harvest management strategies were developed separately in the Atlantic and Mississippi Flyways (Heusmann and Sauer 2000, Chasko and Brakhage 1990, Mississippi Flyway Council 1994). Currently, the Mississippi Flyway uses a double-looping process and the Atlantic Flyway uses multi-stock management for which harvest estimates from wood duck banding data are used to set regulations annually (USFWS 2022, Garretson 2021). Greenawalt et al. (2022) demonstrated sufficient spatial variability in wood duck harvest rates among some banding locations and raised concerns that declining banding effort in the southeastern United States, where harvest rates are higher, would reduce precision of estimates. This uneven distribution of banding among states may bias demographic rate estimates if band deployment locations vary over time, potentially leading to biased harvest management decisions. Because wood ducks remain one of the most harvested waterfowl species in eastern North America without a comprehensive population survey (Fronczak 2021, Raftovich et al. 2022, Garrettson

2023), we sought to (1) quantify spatial variation in survival and harvest rates of wood ducks at multiple scales across North America, (2) identify appropriate population delineations and monitoring units based on this variation, and (3) provide updated banding goals to support robust inferences for harvest management.

STUDY AREA

Our study included wood ducks banded in the U.S. and Canadian portions of the Mississippi and Atlantic Flyways (Table 1). These states and provinces encompass the entire wood duck annual range (i.e., breeding and wintering) in eastern North American (Bellrose and Holm 1994).

METHODS

Band-recovery data

Wood ducks were captured during the pre-season (July-September) period by state and federal agencies and individually marked with United States Geological Survey (USGS) aluminum leg bands. Capture methods used baited traps, including swim-in traps (Dieter et al. 2009), rocket nets, and walk-in confusion traps (Sharp and Smith 1986). Upon capture, wood ducks were sexed and then aged as either hatch year (hereafter: juvenile) or after hatch year (hereafter: adult) by plumage characteristic and cloacal examination (Carney 1992). These characteristics establish four cohorts of wood ducks Adult Female (AF), Adult Male (AM), Juvenile Female (JF), and Juvenile Male (JM). Recovery data including location was then obtained in the form of citizen science when banded birds were harvested by waterfowl hunters or found dead and the uniquely marked band was reported to the USGS Bird Banding Laboratory (BBL).

We downloaded wood duck banding data (deployments and recoveries) from the USGS BBL from 1960-2022 (Celis-Murillo et al. 2022). We limited bandings and recoveries to include birds banded 2000–2021 during the pre-season period (July – September; Balkcom et al. 2014) and recovered 2000-2022, making the 2021–2022 hunting season the last included. We limited data to this range given the dates of the last major distribution study (Kelley 1997); to limit effects of landscape change, changes to agencies policies influencing band deployment, changes to BBL data collection methodologies, or other external factors that could have occurred over a longer period of time; and to facilitate comparisons with recently completed work (Garrettson 2021, Greenawalt et al. 2022).

For both bandings and recoveries, we excluded birds of unknown age or sex (Garrettson 2007, Garrettson 2021, Greenawalt 2023), birds that were banded as locals (i.e., flightless) due to differential survival from flighted juveniles (Hestback et al. 1989), and birds banded in nest boxes as they may have differential survival and recovery rates (Balkcom et al. 2014, Garrettson 2021). We included only birds banded under status codes not expected to influence survival or band reporting rates: normal wild (BBL status code = 3), birds that were only marked with federal numbered leg bands (BBL code = 00), control birds in a reward band study (BBL code = 04), and birds that were night-lighted (BBL code = 70). We included only recoveries recorded as shot (BBL how code = 1) or found dead (BBL how code = 0; Garrettson 2021).

As one hunting season includes two calendar years, we converted recovery year to recovery season. For recoveries in which the recovery month was specified, birds recovered from September – December, the recovery season equaled the recovery year, and for birds recovered January – February the recovery season was recovery year -1 (Garrettson 2021, Garrettson and Howard 2023, Greenawalt 2023). We included recoveries listed as fall (BBL month code = 93), or hunting season (BBL month code = 94), and for those the recovery season was the recovery year. We also included recoveries listed as spring (BBL month code = 83) and the recovery season was recovery year -1. We excluded recoveries listed as unknown month of encounter (BBL month code = 99). Recoveries were included regardless of who reported them or the method by which they were reported (e.g., phone or web; Garrettson 2021, Greenawalt et al. 2022). We excluded any birds not meeting recovery criteria from the band release data.

Mark-recovery model

Following methods used by Greenawalt et al. (2022), we used a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. For each year (*t*) and spatial stratum (*k*), we estimated sex (*l*), and age (*m*) specific (i.e., cohorts) band-recovery probabilities ($f_{t,k,l,m}$) as a function of hunting mortality (i.e. harvest; $Hm_{t,k,l,m}$), crippling loss (*cL)*, and time-specific band-reporting probabilities (p_t) from 2000–2022 (Greenawalt et al . 2022, Riecke, unpublished).

$$f_{t,k,l,m} = Hm_{t,k,l,m} \; x \; p_t \; x \; (1 - cL)$$

We assumed a constant crippling loss of 0.2 throughout the study period for all cohorts (Martin and Carney 1977, Hicklin and Barrow 2004, Schulz et al. 2006). We used time-specific band reporting probabilities (p_t) from 2000–2022, transforming means and standard deviations of annual band reporting probability estimates to shape parameters of a beta distribution using moment matching (Hobbs and Hooten 2015, Thompson et al. 2022, Greenawalt 2023). Band reporting probabilities were then included as informative priors.

We modeled harvest and natural mortality with a grand mean for each cohort and stratum and a random year effect. Cohort and stratum specific grand mean hunting and natural mortality were modeled using vague priors on the probability scale and transformed to the logit scale to include the random effect:

$$Mean.Hm_{t,k,l,m} \sim Beta(1,1)$$

$$Mean.Nm_{t,k,l,m} \sim Beta(1,1)$$

$$logit(Hm_{t,k,l,m}) \sim Normal(logit(Mean.Hm_{t,k,l,m}), \sigma^2_{Hm,k,l,m}),$$

$$\sigma_{Hm,k,l,m} \sim Uniform(0,2)$$

$$logit(Nm_{t,k,l,m}) \sim Normal(logit(Mean.Nm_{t,k,l,m}), \sigma^2_{Nm,k,l,m}),$$

$$\sigma_{Nm,k,l,m} \sim Uniform(0,2)$$

where $Mean.Hm_{t,k,l,m}$ and $Mean.Nm_{t,k,l,m}$ are the grand mean for hunting and natural mortality, $\sigma^2_{Hm,k,l,m}$ and $\sigma^2_{Nm,k,l,m}$ are the variance for the random year effect for hunting and natural mortality, and $\sigma_{Hm,k,l,m}$ and $\sigma_{Nm,k,l,m}$ are the standard deviations for the random year effect of hunting and natural mortality for each spatial stratum (*k*), sex (*l)*, and age (*m*). We calculated survival as a function of hunting ($Hm_{t,k,l,m}$) and natural mortality ($Nm_{t,k,l,m}$):

$$S_{t,k,l,m} = 1 - Hm_{t,k,l,m} - Nm_{t,k,l,m}$$

We formatted band-recovery data into m-arrays and analyzed with a multinomial likelihood to reduce computational requirements (Brownie 1985, Kéry and Schaub 2012). Each row was modeled as a multinomial trial with the number of released individuals in each year as the index (Kéry and Schaub 2012). Multinomial cell probabilities denote the probability of being recovered from release occasion until the end of the study and the probability of never being recovered. Therefore, cell probabilities are functions of survival ($S_{k,l,m}$) and recovery ($f_{k,l,m}$) parameters for each stratum (k), sex (*l*), and age (*m*). We assumed birds banded as juveniles had the same survival and recovery probabilities as adults once they "graduated" into that cohort the following spring. Direct recoveries for both adults and juveniles were a function of recovery probabilities ($f_{k,l,m}$) for each cohort. For adults, subsequent indirect recovery cell probabilities were a function of annual survival and recovery:

$$\left(\prod_{t=1}^{t-1} S_{t,k,l,m}\right) f_{t,k,l,k}$$

For juveniles, subsequent cell probabilities were a function of the survival ($S_{hy,k,l}$) in the first year as a juvenile and then survival ($S_{ahy,k,l}$) and recovery probabilities ($f_{ahy,k,l}$) as an adult:

$$S_{hy,t=1,k,l} f_{ahy,t,k,l}$$

$$S_{hy,t=1,k,l}\left(\prod_{t=2}^{t-1} S_{ahy,k,l}\right) f_{ahy,t,k,l}$$

The probability of never being recovered was calculated as 1 minus the sum of the probabilities of begin recovered for individuals of the same release year. Where S_{ahy} and f_{ahy} are the survival and recovery probabilities of adults, and S_{hy} and f_{hy} are the survival and recovery probabilities of juveniles.

Spatial variation in harvest rates

To quantify spatial variation in demographic rates, we created 12 different regional sub-divisions (Table 2). We fit the model to each of the 12 different regional sub-divisions, each with a varying number of spatial strata (k) dependent on the number of regions in that division (i.e., Kelley (1997) regions k = 6, North vs. South k = 2, etc.). To quantify the spatial variation in harvest rates, we used the coefficient of variation within and among the spatial strata to calculate a ratio for each of the 12 regional subdivisions:

$$\text{Variation Ratio} = \frac{Hm\ CV\ Among\ Strata}{Hm\ CV\ Within\ Strata}$$

We wanted to maximize the variation among regions while minimizing the variation within a region. Therefore, we ranked the 12 different scenarios from best (greatest variation ratio) to worst (smallest variation ratio) to determine the most appropriate scale for providing banding goals.

Simulations

To understand how banding deployment distributions could affect future wood duck demographic estimates within the current management paradigm (i.e., Flyway-scale), and our third-ranked sub-division (Three Latitudinal Regions, see results below; Figure 1b), and at a smaller, intersected Flyway by Latitudinal Region scale (Figure 1c), we simulated varying banding efforts across 24 different banding scenarios at those three scales (i.e., Flyway, Three Latitudinal Regions, and Atlantic or Mississippi Flyway Latitudinal Regions scale; Table 3). We simulated band-recovery data based on estimated demographic rates for each cohort in each region. For each scenario, we assigned a total number of bands to each region; cohort-specific banding numbers were then calculated based on the cohort's current percentage of banded samples. These cohort percentages were based on the average banding frequency and cohort percentage in each determined region from 2016–2021 (Table 4–5).

We simulated mark-recovery data using the banding numbers and random values for demographic rates drawn from beta distributions of hunting mortality (*Hm*) and natural mortality (*Nm*) that were specific to that geographic region or strata (*k*; Table 6–7).

$$Nm_{k,l,m} \sim beta\left(a_{Nm,k,l,m}\, , \beta_{Nm,k,l,m}\right),$$

$$Hm_{k,l,m} \sim beta(a_{Hm,k,l,m}, \beta_{Hm,k,l,m}),$$

For the simulations we used a reporting rate of 0.84 and SD = 0.03 to calculate shape parameters for a beta distribution (Greenawalt et al. 2022, Riecke, unpublished).

$$p_t \sim beta(a_{p_t}, \beta_{p_t})$$

We generated random numbers from a multinomial distribution to create the mark-recovery data for each stratum, age, and sex class.

To obtain single estimates for each Flyway, we simulated band recovery for each of our identified regions divided by flyway and then combined the data for the entire flyway (i.e., strata (*k*) = 1). For our Three Latitudinal Regions and the Atlantic or Mississippi Flyway Latitudinal Regions, we again simulated data for each region, but then modeled demographic rates separately. We simulated each banding scenario 100 times for a five-year period and fit the simulated banding data to the mark-recovery model. We calculated bias for demographic rates from each iteration of the simulation and then summarized across the 100 simulations:

$$Bias = \left|\frac{demographic\ parameter\ estimate - simulated\ truth}{simulated\ truth}\right|$$

We also calculated CV for estimates of harvest rates for each scenario. We sought to provide banding recommendations that meet a ≤7% five-year mean CV precision threshold (Garrettson 2021). We identified banding goals at our Three Latitudinal Regions scale, Atlantic Latitudinal Regions scale, and the Mississippi Latitudinal Regions scale based on the banding distributions that reached the desired precision threshold. We used a logarithmic regression to assess how the number of band deployments from our simulations related to harvest rate CV's (i.e., band deployments ~ log (harvest rate CV). We provided banding goals similar to Collins et al. (2023), which is a total banding number that encompasses the given cohort, given its percentage of the observed banded sample. For example, if 2,000 adult females need to be banded to reach adult female precision levels and this cohort makes up 20% of the banded sample, our recommended goal for the given area would be 10,000 total bands deployed.

Computations

We conducted all analysis in JAGS (Plummer 2003) using the "jagsUI" package (Kellner 2019) in R 4.2.2 (R Core Team 2022). We ran three Markov chain Monte Carlo (MCMC) chains for 150,000 iterations and discarded the first 50,000 iterations as a burn-in and then retained every 50th iteration. We then visually assessed trace plots and MCMC chains for convergence and used the Brooks-Gelman-Rudin statistic ($\hat{R}$) < 1.01 as an assessment of convergence (Brooks and Gelman 1998).

RESULTS

Over our 22-year study period, 611,148 preseason bands were deployed on wood ducks meeting our inclusion criteria. Of those, 183,018 (29.9%) were banded in the Atlantic Flyway and 428,130 (70.1%) were banded in the Mississippi Flyway. Of bands deployed, 99,777 (16.3% of deployments) were recovered fitting our inclusion criteria. Of recovered bands, 13,242 (13.3%) were recovered in a Flyway different than they were banded in; 6,765 (6.8%) birds banded in the Mississippi were recovered in the Atlantic Flyway, and 3,462 (3.5%) birds banded in the Atlantic were recovered in the Mississippi Flyway. In addition, 3,015 (3.0%) of birds were recovered in the Central Flyway, of those 110 were banded in the Atlantic Flyway.

Spatial variation in harvest rates

At the Flyway scale, we found similar mean harvest rates in the Atlantic (AF 0.085, AM 0.131, JF 0.140, JM 0.174) and Mississippi (AF 0.084, AM 0.122, JF 0.128, JM 0.166; Table 8-9; Appendix A9) Flyways for each cohort. However, at the Flyway scale, geographic demographic rate variability was masked, and the Flyway scale ranked poorly in our sub-division comparisons (CV ratio = 2.34; Rank = 10; Table 2). Our top-ranking sub-division was the Equal Break, Three Latitudinal Bins which encompassed both Flyways (CV ratio = 4.83; Rank = 1; Table 2; Figure 1a). Importantly, at this scale we observed higher mean harvest rates in our northernmost bin (AF 0.100, AM 0.136, JF 0.164, JM 0.202) and lower mean harvest rates in our southernmost bin (AF 0.063, AM 0.098, JF 0.084, JM 0.117; Appendix A6), especially in the juvenile cohorts. Our third ranked (second ranked that included Canada) subdivision was the Three Latitudinal Regions scale (CV ratio = 4.52; Table 2; Figure 1b). The Three Latitudinal Regions scale consists of three regions grouped by states and Canadian provinces. The northern region consists of Minnesota, Iowa, Wisconsin, Michigan, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, Vermont, Maine, Ontario, Quebec, New Brunswick, Prince Edward Island, and Nova Scotia. The central region consists of New Jersey, Pennsylvania, West Virginia, Virginia, Maryland, Delaware, Ohio, Indiana, Illinois, Missouri, Kentucky, Tennessee, Arkansas, and North Carolina. The southern region consists of South Carolina, Georgia, Florida, Alabama, Mississippi, and Louisiana.

Any sub-division we created with bins along a longitudinal gradient (east to west) encompassing both Flyways ranked poorly (Table 2). For example, our Equal Break, Five Longitudinal Bins, U. S., which encompassed both Flyways ranked eleventh (Table 2). The Kelley (1997) scale only had notable variation in mean harvest rate between northern and southern regions (Table 8-9; Appendix A2), with little variation in harvest elsewhere.

Specifically, the juvenile male cohort harvest rates were within 0.8% between the North East (0.196) and North Central (0.188) regions, and only 2.2% different between the Southern (0.146) and South East (0.124) regions. The Kelley (1997) regions ranked eighth (CV ratio = 2.86) among our sub-division's comparison (Table 2).

Simulations

Flyway scale

Grouping simulated data across the Atlantic Flyway, we found the current banding distribution and frequency is reaching mean harvest rate CV targets for all cohorts except adult females (AF 7.4%, AM 5.0%, JF 6.0%, JM 5.03%; Figure 2). Shifting band distributions northward increased estimated mean harvest rates and shifting band distributions southward decreased estimated mean harvested rates. However, the change in mean harvest rates was less intense. For example, shifting 70% of bands to our identified northern region created only marginally higher mean harvest rates (AF 0.087, AM 0.133, JF 0.144, JM 0.181) than shifting 70% of bands to our identified southern region (AF 0.072, AM 0.113, JF 0.121, JM 0.152; Figure 2)

Grouping simulated data across the Mississippi Flyway, we found the current banding distribution is meeting the mean harvest rate CV targets for all cohorts (AF 5.4%, AM 3.8%, JF 4.2%, JM 3.6%; Figure 4; Table 4)). Shifting banding distribution within the Mississippi Flyway affected mean harvest rate estimates; as band distribution shifted northward, harvest rates increased, with the opposite effect occurring if distributions shifted to the south. For example, shifting 70% of bands to our identified northern region produced higher mean harvest rates (AF

0.10, AM 0.13, JF 0.15, JM 0.19; Figure 2) than the scenario that shifted bands 70% to our identified southern region (AF 0.07, AM 0.11, JF 0.10, JM 0.13; Figure 4).

Three Latitudinal Regions scale

At our identified Three Latitudinal Regions scale (Figure 1b) there was little change in mean estimated harvest rates across simulations within the three regions (Figure 6). However, certainty around our parameter estimates varied with regional banding efforts (Figure 6). The current banding distribution at the Three Latitudinal Regions scale meets desired precision thresholds across all regions and cohorts except in the southern region for adult (10.42 % CV) and juvenile (8.87% CV) females (Figure 6). Based on our simulations, the southern region would need to increase by 200% to ≥11,000 band deployments to reach ≤7% CV for juvenile female harvest rates, and by 250% to at least 14,000 band deployments for adult female harvest rates (Figure 6).

At the Three Latitudinal Regions scale, there was little change in the mean bias of our parameter estimates as less bands were allocated to a given region (Figure 7). For example, allocating 50% of bands to the north, 25% to the central region, and 25% to the southern region lead to a mean bias of 0.04, 0.07, and 0.08 for each respective region. Shifting banding distribution to 25% of bands to the north, 25% to the central region, and 50% to the southern region lead to a mean bias of 0.06, 0.07, and 0.07 for each region. For all scenarios, regions, and cohorts at this scale, the mean bias ranged from 0.03 to 0.10, and both female cohorts had slightly higher levels of bias (Figure 7).

Mississippi Flyway Latitudinal Regions scale

The Mississippi Flyway on average currently deploys 20,473 bands annually with 44.3%, 34.8%, and 21.0% of deployments being in our identified northern, central, and southern regions (Table 4). The current distribution and frequency does not meet mean harvest CV target levels for the adult female cohort in any region (north 7.54% CV, central 8.68% CV, south 17.78% CV), for adult males in the central (7.20% CV) and southern region (8.53% CV; Figure 8), or either juvenile cohorts in the southern region (JF 9.67%, CV JM 8.00% CV). Based on our scenarios, band deployments in the Mississippi Flyway would need to be increased ≥50% (10,000 bands) for the northern and central regions and ≥70% (14,000 bands) in the southern region (Figure 8). In addition, to reach mean harvest rate precision levels for juvenile females, the southern region would need to increase ≥50% (10,000 bands) more than current band deployments.

For our simulations at the Mississippi Flyway by Latitudinal Region scale, we observed small changes in the mean bias of our parameter estimates as less bands were allocated to a given region (Figure 9). For example, for the adult female cohort when allocating 50% of bands in the north, 25% in the central, and 25% in the southern region lead to mean bias in estimates of 0.06, 0.08, and 0.10 for those regions. Switching this distribution to 25% of bands in the north, 25% in the central, and 50% in the southern region lead to mean bias in estimates of 0.07, 0.08, and 0.09 for those regions. For all scenario's, regions, and cohorts at this scale the mean bias in our parameter estimates ranged from 0.04 to 0.10, with highest amount of bias occurring in adult female cohort and the lowest occurring for adult and juvenile males.

Atlantic Flyway Latitudinal Regions scale

The Atlantic Flyway on average currently deploys 7,823 bands annually with 29.6%, 54.1%, and 16.4% of deployments being in our identified northern, central, and southern regions

(Table 4), which only reaches acceptable precision levels for juvenile males in the central region (6.26% CV). Importantly, the current banding distribution and frequency does not reach adult female (north 14.36 %, central 10.22 %, south 16.32% CV) or adult male (north 7.33%, central 7.77%, south 11.93% CV) mean CV targets in any region (Figure 10). To reach targets for adult females, the Atlantic Flyway would need to increase banding to at ≥11,000 in the north, ≥10,500 in the central, and ≥15,000 in the south regions. To reach ≥7% CV for adult males, the Atlantic Flyway would need to band ≥2,500 bands in the north, ≥6,000 in the central, and ≥7,000 in the southern regions.

The bias in our parameter estimates was slightly higher than that of simulations at the previous scales (Figure 11). For example, for the adult female cohort, allocating 50% of current band numbers in the north, 25% in the central, and 25% in the southern regions, resulted in mean bias estimates of 0.08, 0.11, and 0.13 for those regions. Shifting distribution to 25% of bands in the north, 25% in the central, and 50% in the southern region leads resulted in mean bias estimates of 0.011, 0.10, and 0.11 for those regions. For all scenario's, regions, and cohorts at this scale the mean bias ranged from 0.04 to 0.23, with highest amount of bias occurring in juvenile female parameter estimates and the lowest occurring for adult males. Our banding recommendations for adult females and males for all scales and regions are provided (Table 10).

DISCUSSION

Our analysis of wood duck demographic rates across Flyways reveals regionally variable juvenile harvest rates, aligning with past evidence of demographic differences across breeding latitudes (Bowers and Martin 1975, Nichols and Johnson 1990, Garrettson 2007, 2021). Our data concurs with Greenawalt et al. (2022) suggesting Flyway-scale analysis of harvest and survival rate without controlling for band deployment geography masks subtle demographic differences latitudinally that could be impactful to harvest management decisions if deployment distribution shifts over time. However, we found no longitudinal variation in demographic rates, suggesting consolidation of some administrative boundaries across flyways is viable. Delineating regions by latitude balances precision with practicality for setting banding goals and further stepping down quotas to states or smaller geographies (Yerkes 2000, Wilson et al. 2022). Specifically, latitudinal bins address the 9% north-south juvenile mean harvest rate difference, while merging states/provinces eases implementation (Garrettson and Howard 2023). Our simulations highlight risks of biased flyway-level demographic rates if band deployment shifts spatially, which is has in the past and is likely to do in the future (Raftovich et al. 2018). For example, decreased southern deployments could inflate the effect of greater northern harvest rates, while southern concentration could underestimate northern take. Maintaining representative sampling across breeding latitudes and a weighted analysis by breeding region are essential for unbiased demographic rates at the flyway scale (Kaminski and Gluesing 1987, Anderson and Anderson 2005).

Interestingly, we found the Kelley (1997) regions within Flyway subdivisions exhibit little demographic variation, which questions the past reliance on these boundaries for setting banding goals and quotas (Kelley 1997, Raftovich et al. 2018). Meanwhile, banding efforts have significantly decreased in portions of the southeastern U.S. in recent years (Greenawalt et al. 2022) and constraints on state and federal agencies due to funding and staffing limitations will likely continue to reduce banding effort across the region (Jacobson et al. 2007). Extreme cases, e.g., when bands deployed in the southern Atlantic region represent only 5% of total bands, resulted in mean harvest rate CV's over 25% for both the female cohorts and failed to meet the precision threshold for all cohorts in two of our three regions. Given that the southern Atlantic region bands approximately 16% of the wood ducks in the Flyway annually and its relative contribution has been declining, this is not an unreasonable scenario in the future. Declining spatially representative sampling amplifies the need to re-evaluate management units based on updated biological data rather than traditional political boundaries.

Our recommended higher banding goals for adult females aim to rectify their under-representation despite lower recovery rates, although meeting targets will be challenging (Garrettson 2021, Raftovich et al. 2015). Striving to attain adult female precision levels will only increase the robustness of wood duck banding programs and analysis, while ensuring precision targets are being met for all other cohorts. However, combining Flyway estimates would require less overall banding than independent goals (Alisauskas et al. 2006). As shown in our Flyway-level simulations imbalanced banding could still bias Flyway-level rates, underscoring the need for equitable latitudinal sampling (Arnold et al. 2012). Considering the findings of our analysis we do believe the distributions of bands within a singular region will affect demographic rate estimates. However, to provide further guidance to the flyways in an equitable manner region goals could be stepped down to the state/province level using similar methods outlined in Garrettson and Howard (2023). Specifically, using the area of wooded wetlands as a proxy for wood duck habitat to weight goals for individual states or provinces in each region.

Ultimately, our integrated analysis provides a roadmap for efficient banding that balances precision and practicality. Although current banding distribution and analysis at the Flyway scale are largely meeting mean harvest rate precision goals, the significantly different demographic rates of wood ducks breeding at northern vs. southern latitudes is not currently accounted for. Regional goals based on latitude offer a biologically relevant framework for harnessing mark-recapture data (Sofaer et al. 2019). As there are currently no other means to monitor this species in the majority of its breeding range (Zimmerman et al. 2015, 2017), it is critical to ensure all subsets of the population are represented in banding distributions. In addition, this will allow for periodic abundance estimates from bands to further strengthen integrated management attuned to demographic nuances underlying this widespread species.

MANAGEMENT IMPLICAITONS

Our integrated analysis provides guidance for optimizing banding programs to support informed wood duck management. First, delineating regional goals by latitude offers a biologically relevant framework, capturing demographic variation missed by traditional boundaries. However, current distribution shortcomings like declining southeastern sampling could produce biased estimates if unaddressed. Maintaining balanced, representative sampling across breeding latitudes is essential to provide accurate regional and Flyway-level insights. Second, the substantially higher banding goals we recommend for under-represented adult females will increase cohort precision and representativeness. However, coordinated Flyway-level goals can achieve desired precision with fewer total bands deployed. Finally, periodic integrated abundance estimates from banding data are needed to complement existing harvest surveys. Overall, our findings provide a roadmap to harness banding programs through efficient, representative sampling that accounts for subtle demographic variation - ensuring robust mark-recapture data to guide integrated wood duck management

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Table 1. The States and Provinces of eastern North America divided by administrative Flyway and wood duck banding reference areas from Kelley (1997).

Geographic Scale	Sub-Regions	States and Provinces
Atlantic Flyway	Northern Atlantic	Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island, Maine, Vermont, New Hampshire, Massachusetts, New York, Connecticut, Rhode Island, Pennsylvania
	Southern Atlantic	New Jersey, West Virginia, Virginia, Maryland, Delaware, North Carolina, South Carolina, Georgia, Florida
Mississippi Flyway	Northern Mississippi	Minnesota, Wisconsin, Michigan, Iowa, Illinois, Indiana, Ohio, Missouri
	Southern Mississippi	Kentucky, Arkansas, Tennessee, Mississippi, Alabama, Louisiana
Kelley (1997) Regions	North East	Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, and Pennsylvania, Ontario, Quebec, New Brunswick, Nova Scotia, and Prince Edward Island
	Mid Atlantic	New Jersey, Maryland, Delaware, Virginia, West Virginia, North Carolina, South Carolina
	Southern	Kentucky, Tennessee, Arkansas, Louisiana, Alabama, Mississippi
	Southeastern	Georgia, Florida
	Lake States	Michigan, Indiana, Ohio
	North Central	Minnesota, Wisconsin, Iowa, Illinois, Missouri

Table 2. Regional divisions created to asses demographic rate variability of preseason banded wood ducks in eastern North America from 2000–2022. These regions include Mississippi and Atlantic Flyways, the number of strata (*k*) created in each sub-division, and each sub-division coefficient of variation (CV) rank according to our harvest CV ratio. This ratio was calculated by dividing the coefficient of variation among by the coefficient of variation within the spatial strata and each sub-division was ranked from best (greatest variation ratio) to worst (smallest variation ratio).

Sub-Division	Description	Number of Strata (*k*)	CV Rank
Equal Break, Three Latitudinal Bins	The U. S. and Canadian portions of the Mississippi and Atlantic Flyways divided into three bins using an equal break sequence between the minimum and maximum latitude of banding locations.	3	1
Equal Break, Three Latitudinal Bins, U. S.	The U. S. portion of the Mississippi and Atlantic Flyways divided into three bins using an equal break sequence between the minimum and maximum latitude of banding locations.	3	2
Three Latitudinal Regions	The U. S. and Canadian portions of the Mississippi and Atlantic Flyways divided into three regions by state and province based on the latitudinal lines from the three latitudinal bin division that includes Canada.	3	3
Equal Break, Five Latitudinal Bins, U. S.	The U. S. portion of the Mississippi and Atlantic Flyways divided into five bins using an equal break sequence between the minimum and maximum latitude of banding locations.	5	4
Three State Latitudinal Regions	The U. S. portion of the Mississippi and Atlantic Flyways divided into three regions by state based on the latitudinal lines of the Three Latitudinal Bin division.	3	5
Northern and Southern Regions	The U. S. and Canadian portions of the Mississippi and Atlantic Flyway divided by state and providence from Garrettson 2007.	2	6
North vs. South Longitudinal Bins	The U. S. and Canadian portions of the Mississippi and Atlantic Flyways divided in half latitudinal. Then divided in to thirds	6	7

	longitudinally using a separate equal break sequence between the minimum and maximum longitude of banding locations for the north and south half.		
Kelley Regions	The wood duck sub-population regions described by Kelley (1997).	6	8
U. S. Flyway Quadrants	The U. S. Portions of the Mississippi and Atlantic Flyways divided by state, Flyway, and North vs. South Region.	4	9
Flyways	The U. S. and Canadian portions of the Mississippi and Atlantic Flyways.	2	10
Equal Break, Five Longitudinal Bins, U. S.	The U. S. portion of the Mississippi and Atlantic Flyways divided into five bins using an equal break sequence between the minimum and maximum longitude of banding locations.	5	11
Equal Break, Ten Longitudinal Bins, U. S.	The U. S. portion of the Mississippi and Atlantic Flyways divided into ten bins using an equal break sequence between the minimum and maximum longitude of banding locations.	10	12

Table 3. Banding distribution simulation scenarios created to evaluate shifts in preseason wood duck banding distributions in eastern North America (Mississippi and Atlantic Flyways combined) including the geographic scale, simulation name, and description.

Geographic Scale	Simulation Name	Description
Three Latitudinal Regions	ENA current split	The current banding distribution and frequency.
	ENA N25, M25, S50	A sum of the current banding totals divided 25% in the north region, 25% in the middle region, and 50% in the south region.
	ENA N50, M25, S25	A sum of the current banding totals divided 50% in the north region, 25% in the middle region, and 25% in the south region.
	ENA N, M25d, S50d	The current banding total in the north region, a 25% decline of bandings in the middle region, and a 50% decline of bandings in the southern region.
	ENA N25d, M, S25d	The current banding total in the middle region, a 25% decline of bandings in the north region, and a 25% decline of bandings in the southern region.
Atlantic Flyway	Atl. even split	A sum of the current banding totals evenly divided (33%) in each region.
	Atl. current split	The current banding distribution and frequency.
	Atl. N25, M25, S50	A sum of the current banding totals divided 25% in the north region, 25% in the middle region, and 50% in the southern region.

Atl. N25, M50, S25	A sum of the current banding totals divided 25% in the north region, 50% in the middle region, and 25% in the southern region.
Atl. N50, M25, S25	A sum of the current banding totals divided 50% in the north region, 25% in the middle region, and 25% in the south region.
Atl. N70, M25, S5	A sum of the current banding totals divided 70% in the north region, 25% in the middle region, and 5% in the south region.
Atl. N85, M10, S5	A sum of the current banding totals dived 85% in the north region, 10% in the middle region, and 5% in the south region.
Atl. N10, M20, S70	A sum of the current banding totals divided 10% in the north region, 20% in the middle region, and 70% in the south region.
Atl. N70, M20, S10	A sum of the current banding totals divided 70% in the north region, 20% in the middle region, and 10% in the south region.
Atl. even 100p	100% of the current banding totals allocated to each region. 7,823 in the north, 7,823 in the middle, and 7,823 in the south.
Atl. 10k each	10,000 bands allocated to each region.

	At. N11k, M10.5k, S15k	11,000 bands allocated to the northern region, 10,500 to the middle, and 15,000 to the south.
Mississippi Flyway	Miss. even split	A sum of the current banding totals evenly divided (33%) in each region.
	Miss. current split	The current banding distribution and frequency.
	Miss. N25, M25, S50	A sum of the current banding totals divided 25% in the north region, 25% in the middle region, and 50% in the southern region.
	Miss. N25, M50, S25	A sum of the current banding totals divided 25% in the north region, 50% in the middle region, and 25% in the southern region.
	Miss. N50, M25, S25	A sum of the current banding totals divided 50% in the north region, 25% in the middle region, and 25% in the southern region.
	Miss. N10, M20, S70	A sum of the current banding totals divided 10% in the north region, 20% in the middle region, and 70% in the south region.
	Miss. N70, M20, S10	A sum of the current banding totals divided 70% in the north region, 20% in the middle region, and 10% in the south region.

Table 4. The average banding distribution, frequency, and percentage of preseason banded wood ducks in our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway from 2016–2021. Banding frequencies are divided by Latitudinal Regions (North, Central, South) within each geographic scale determined using demographic rate variability.

Geographic Scale	Region	Average Yearly Band Deployments	Percentage of Geographic Scale Total
Three Latitudinal Regions	North	11,345	40.09
	Central	11,382	40.09
	South	5,569	19.68
	Total	**28,296**	
Atlantic Flyway	North	2,314	29.58
	Central	4,230	54.07
	South	1,279	16.35
	Total	**7,823**	
Mississippi Flyway	North	9,068	44.29
	Central	7,115	34.75
	South	4,290	20.95
	Total	**20,473**	

Table 5. The average percentage of each wood duck cohort banded in our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway from 2016–2021. Banding frequencies are divided by latitudinal regions (North, Central, South) within each geographic scale determined using demographic rate variability.

		Average Percentage of Banded Sample			
Geographic Scale	Region	Adult Females	Adult Males	Juvenile Females	Juvenile Males
Three Latitudinal Regions	North	11.79	34.79	23.56	29.86
	Central	12.48	12.37	35.12	40.03
	South	16.22	19.33	30.31	34.14
Atlantic Flyway	North	12.63	36.00	22.30	29.07
	Central	14.46	14.63	31.71	39.20
	South	24.82	28.04	20.68	26.45
Mississippi Flyway	North	11.29	34.07	24.30	30.33
	Central	11.97	11.80	35.99	40.24
	South	13.65	16.73	33.19	36.44

Table 6. The estimated average harvest rate and standard deviation (SD) from 2000–2022 of preseason banded wood in our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway. Harvest rate and standard deviations are divided by latitudinal regions (North, Central, South) within each geographic scale determined using demographic rate variability.

		Adult Female		Adult Male		Juvenile Female		Juvenile Male	
Geographic Scale	Region	Harvest	SD	Harvest	SD	Harvest	SD	Harvest	SD
Three Latitudinal Regions	North	0.101	0.004011	0.136	0.004722	0.166	0.008335	0.202	0.007758
	Central	0.086	0.004656	0.123	0.004786	0.127	0.005967	0.165	0.004064
	South	0.063	0.005320	0.100	0.004196	0.084	0.007925	0.118	0.007972
Atlantic Flyway	North	0.091	0.004896	0.137	0.006708	0.151	0.008059	0.188	0.008619
	Central	0.092	0.007566	0.135	0.006150	0.138	0.008476	0.171	0.009481
	South	0.068	0.009298	0.106	0.007239	0.109	0.017123	0.139	0.018923
Mississippi Flyway	North	0.108	0.007348	0.134	0.006248	0.176	0.012302	0.211	0.011942
	Central	0.083	0.005413	0.118	0.005751	0.125	0.007088	0.163	0.006262
	South	0.060	0.006409	0.095	0.005365	0.078	0.007889	0.112	0.009469

Table 7. The estimated average natural mortality rate and standard deviation (SD) from 2000–2022 preseason banded wood in our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway. Natural mortality rates and standard deviations are divided by latitudinal regions (North, Central, South) within each geographic scale determined using demographic rate variability.

		Adult Female		Adult Male		Juvenile Female		Juvenile Male	
Geographic Scale	Region	Natural	SD	Natural	SD	Natural	SD	Natural	SD
Three Latitudinal Regions	North	0.397	0.014950	0.275	0.019409	0.373	0.022947	0.289	0.015862
	Central	0.402	0.030620	0.268	0.019575	0.380	0.023095	0.279	0.019798
	South	0.421	0.028664	0.285	0.032276	0.413	0.043362	0.233	0.030297
Atlantic Flyway	North	0.399	0.030606	0.283	0.025829	0.365	0.035689	0.288	0.027823
	Central	0.390	0.040953	0.267	0.033541	0.368	0.043761	0.293	0.036987
	South	0.406	0.075603	0.291	0.045841	0.274	0.070271	0.211	0.076730
Mississippi Flyway	North	0.394	0.020557	0.269	0.023545	0.379	0.022376	0.290	0.019571
	Central	0.405	0.027126	0.269	0.022201	0.375	0.025611	0.270	0.022842
	South	0.427	0.037303	0.281	0.032403	0.424	0.055590	0.224	0.029351

Table 8. Average estimated survival rates and coefficient of variation (CV) of preseason banded wood ducks wood ducks from 2000-2022 in eastern North America estimated for each Kelley (1997) region and Flyway.

	Adult Female		Adult Male		Juvenile Female		Juvenile Male	
Subpopulation region	Survival	CV	Survival	CV	Survival	CV	Survival	CV
North East[a]	0.508	7.18	0.585	3.34	0.485	7.96	0.524	4.88
Mid-Atlantic[a]	0.526	6.24	0.604	5.88	0.560	9.95	0.595	7.58
Southern[a]	0.513	4.07	0.619	2.97	0.508	7.12	0.600	3.33
South East[a]	0.525	22.51	0.609	13.51	0.494	24.88	0.582	14.81
Lake States[a]	0.503	6.44	0.597	5.90	0.498	10.00	0.512	6.14
North Central[a]	0.506	5.46	0.605	2.51	0.468	5.51	0.533	4.10
Mississippi Flyway	0.508	3.29	0.608	2.79	0.486	5.01	0.540	2.50
Atlantic Flyway	0.512	6.99	0.586	4.18	0.514	6.50	0.548	4.15

[a] Kelley (1997) regions.

Table 9. Average estimated harvest rates and coefficient of variation (CV) of preseason banded wood ducks wood ducks from 2000-2022 in eastern North America, estimated for each Kelley (1997) region and Flyway.

	Adult Female		Adult Male		Juvenile Female		Juvenile Male	
Subpopulation region	Harvest	CV	Harvest	CV	Harvest	CV	Harvest	CV
North East[a]	0.099	5.42	0.142	3.97	0.160	5.87	0.196	4.92
Mid-Atlantic[a]	0.080	9.21	0.125	7.60	0.124	8.42	0.154	9.11
Southern[a]	0.073	7.50	0.106	5.20	0.110	6.32	0.146	5.38
South East[a]	0.067	22.83	0.096	10.66	0.094	30.01	0.124	13.87
Lake States[a]	0.086	7.66	0.132	6.99	0.134	9.12	0.174	7.16
North Central[a]	0.097	7.23	0.128	4.51	0.152	6.43	0.188	5.24
Mississippi Flyway	0.084	5.61	0.122	4.16	0.128	5.00	0.166	4.29
Atlantic Flyway	0.085	6.34	0.131	4.79	0.140	6.22	0.174	5.40

[a] Kelley (1997) regions.

Table 10. Banding recommendations to meet the ≤7% five-year mean coefficient of variation target for preseason banded Adult female and male wood ducks for our identified Three Latitudinal Regions, and Latitudinal Regions by Flyway. Recommendations provided are a total number of deployments given the current percentage each cohort makes of band deployments.

Scale	Region	Adult Female Goal	Adult Male Goal
Three Latitudinal Regions	North	10,498	3,042
	Central	9,912	8,519
	South	11,999	6,534
Mississippi Flyway	North	8,993	3,655
	Central	9,090	7,124
	South	13,530	7,829
Atlantic Flyway	North	9,449	3,306
	Central	8,475	6,397
	South	9,279	6,585

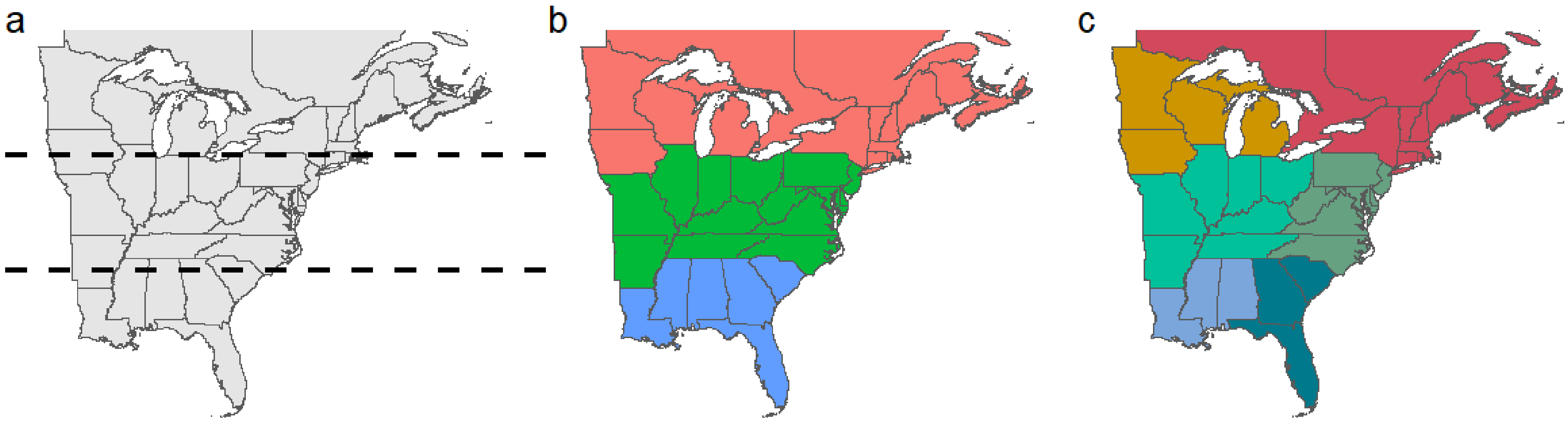

Figure 1. We derived wood duck demographic rates from 2000–2022 from banding data in a mark-recovery framework at varying spatial scales to identify possible new wood duck management regions. We divided eastern North America into various strata to compare demographic rates of wood ducks banded in each. We found that equal break, three latitudinal bins (a) division maximized demographic rate variation between each stratum while minimizing variation within each stratum. From this we created a three latitudinal regions (b) division, dividing states and provinces along those latitudinal lines. We then also divided these regions by Flyway (c) to create six different regions for Flyway administrative purposes.

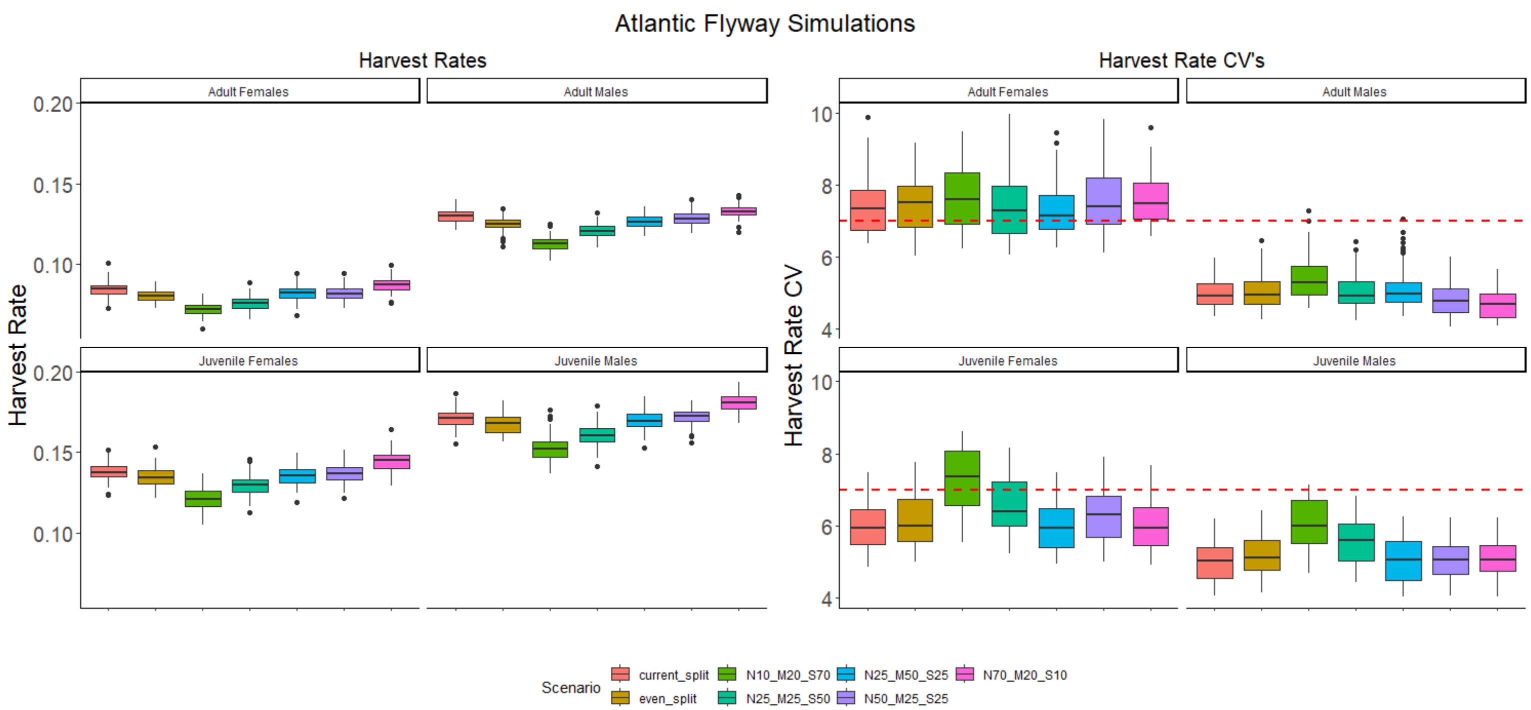

Figure 2. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Atlantic Flyway Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male). Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance.

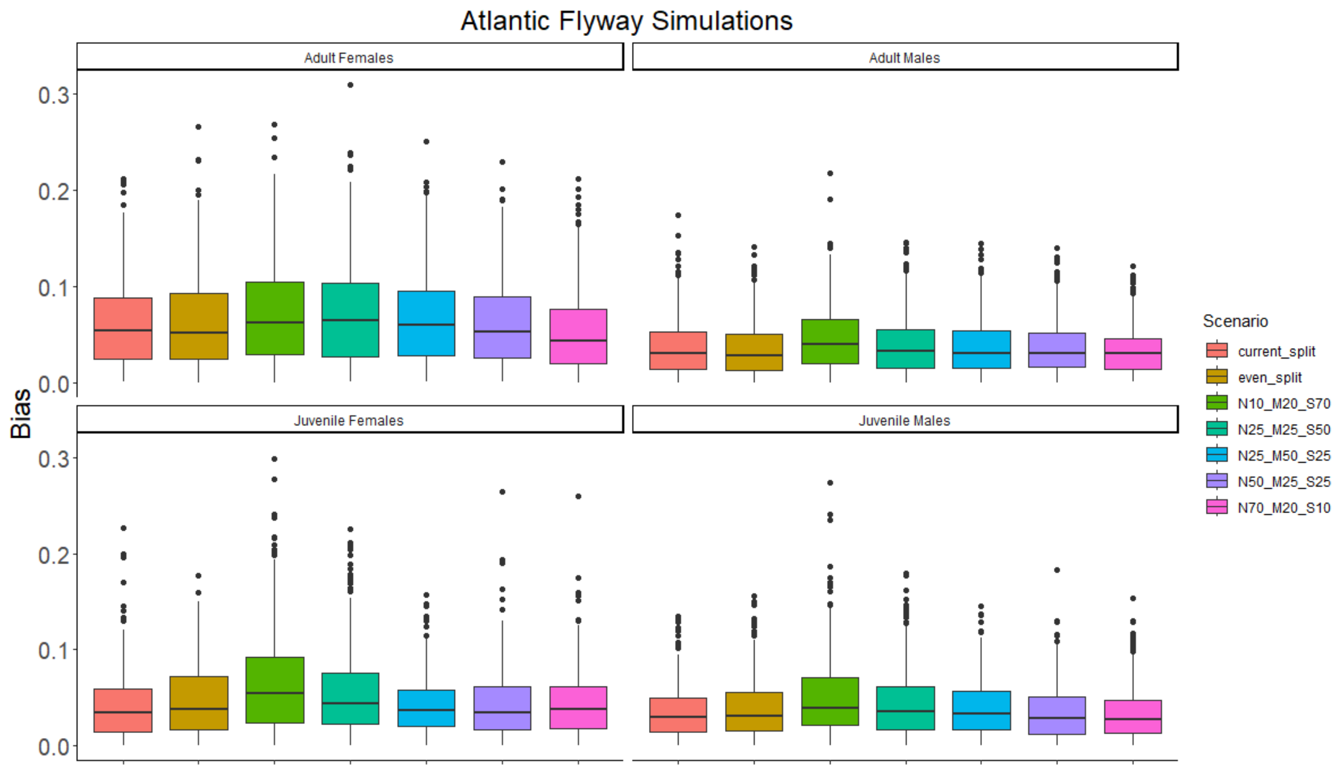

Figure 3. Bias of harvest rate estimates for each Atlantic Flyway Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male). Bias was derived by simulated each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data.

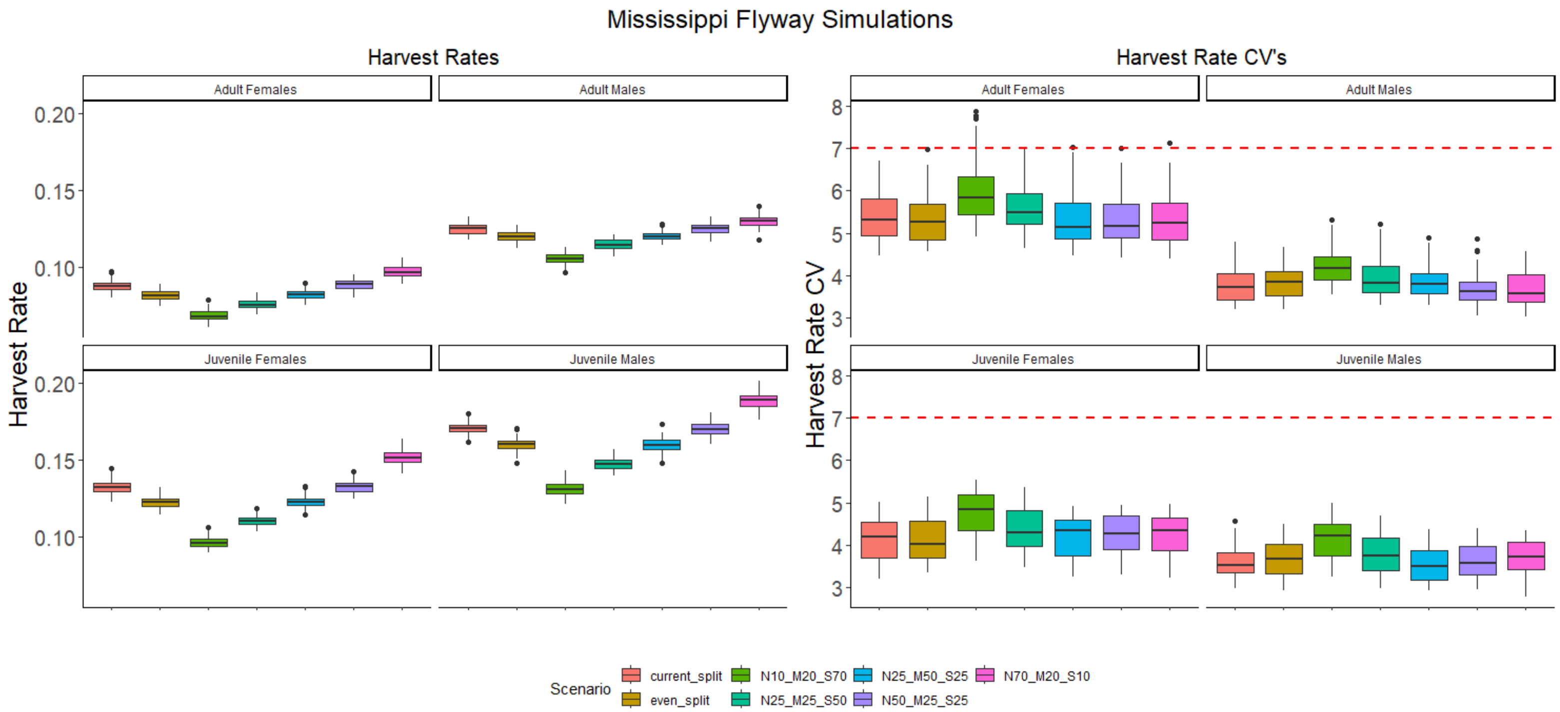

Figure 4. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Mississippi Flyway Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male). Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance.

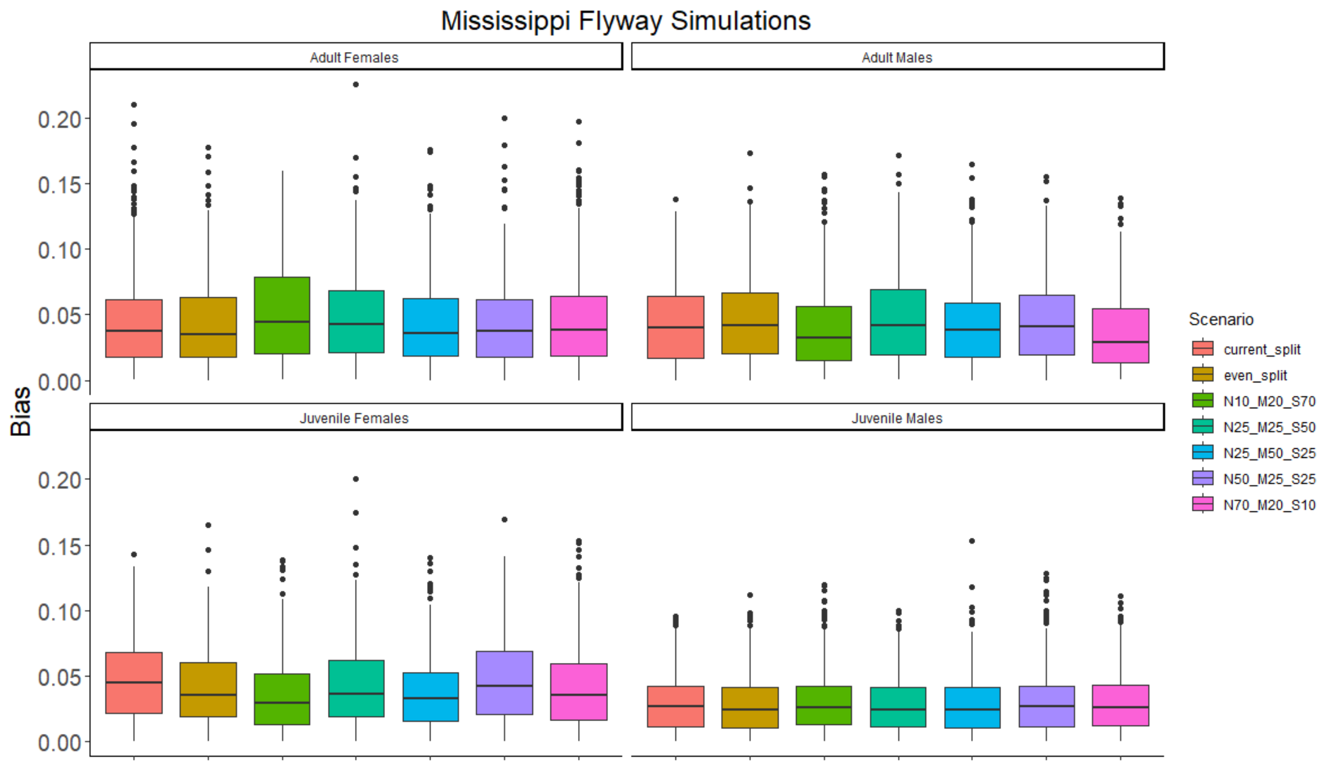

Figure 5. Bias of harvest rate estimates for each Mississippi Flyway Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male). Bias was derived by simulated each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data.

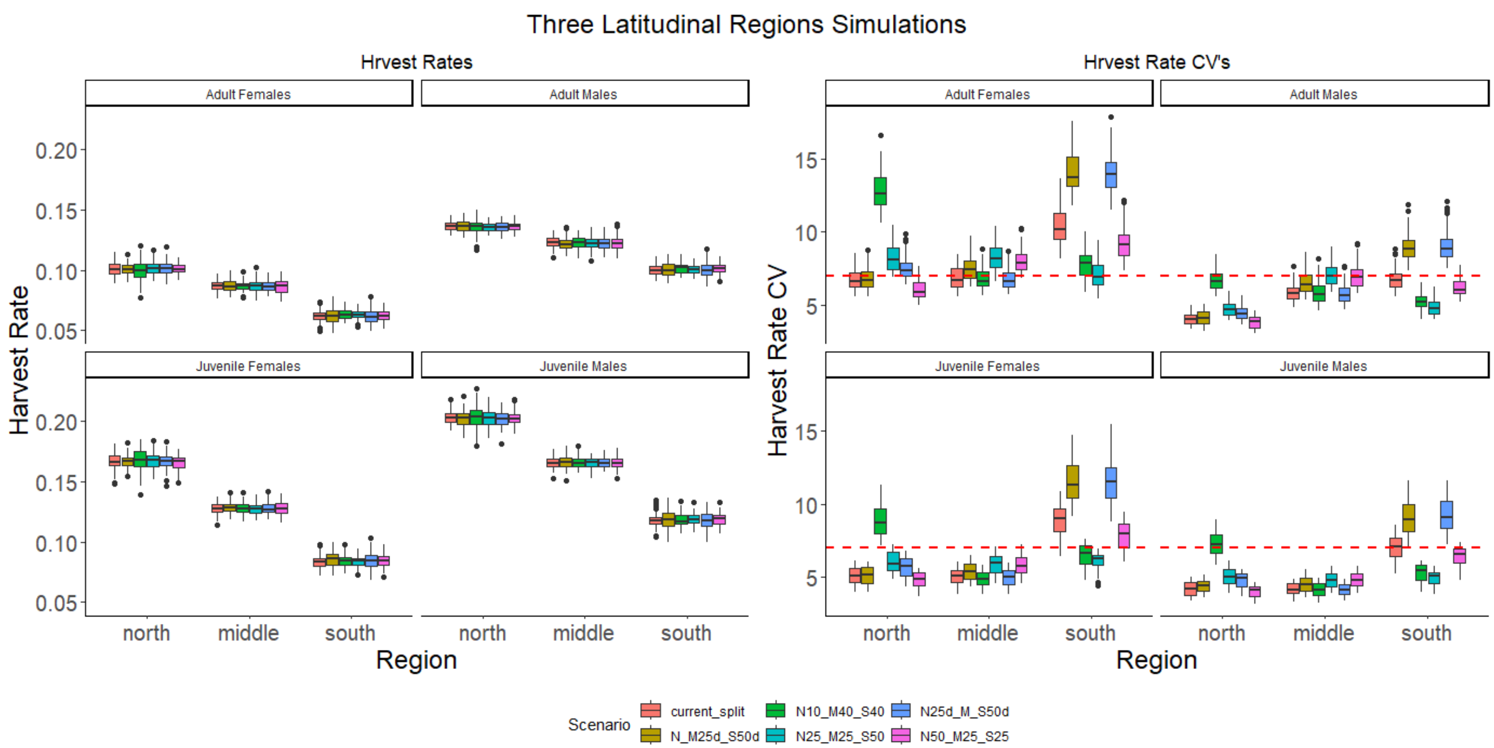

Figure 6. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each of our identified regions. Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance.

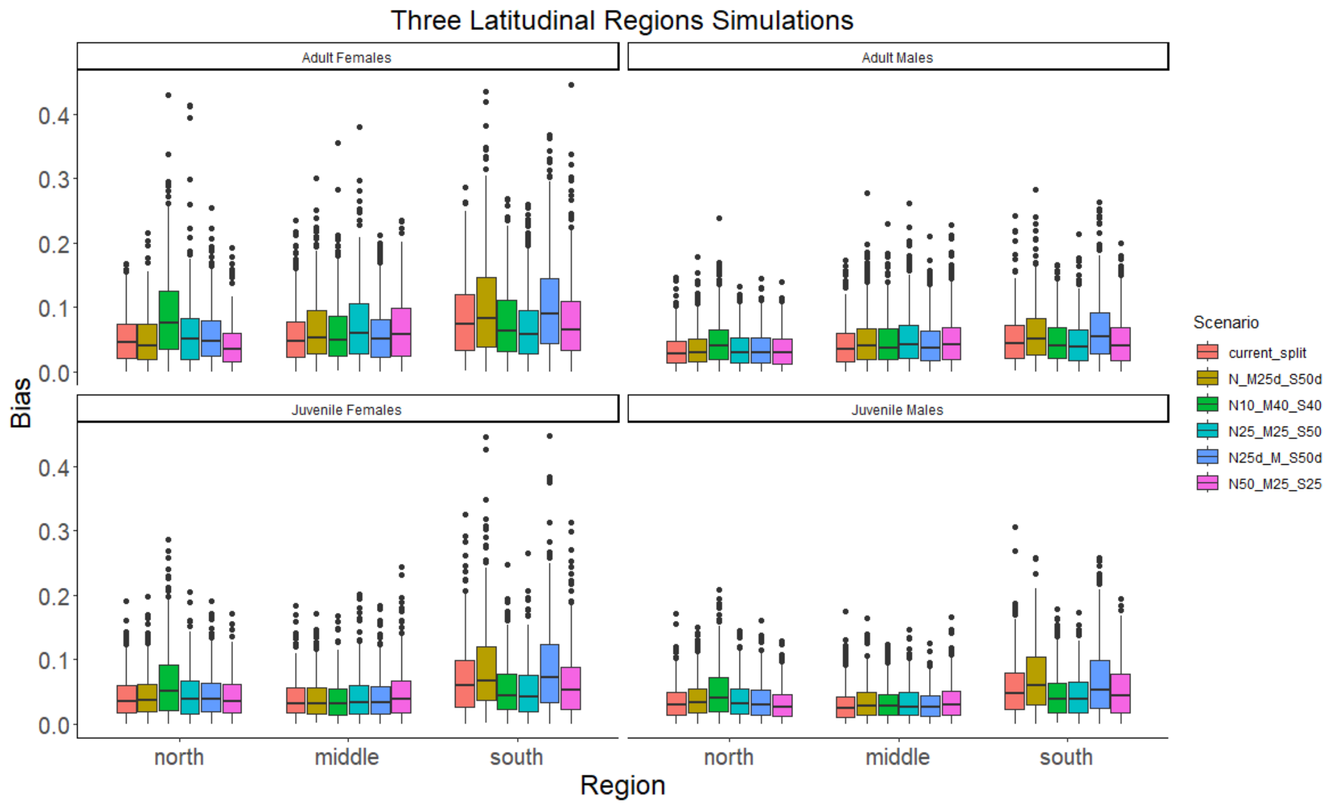

Figure 7. Bias of harvest rate estimates for each Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each region. Bias was derived by simulated each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data.

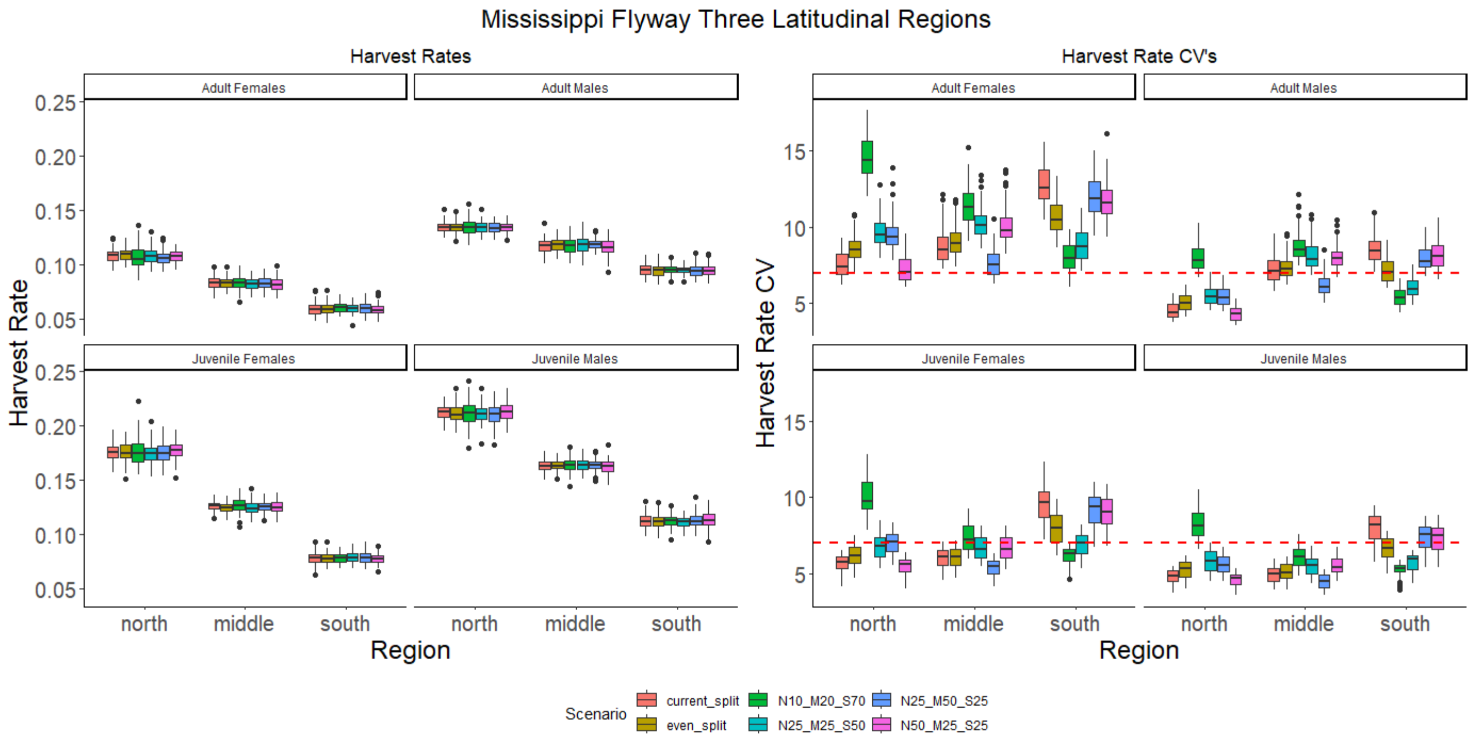

Figure 8. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Mississippi Flyway Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each of our identified regions. Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance.

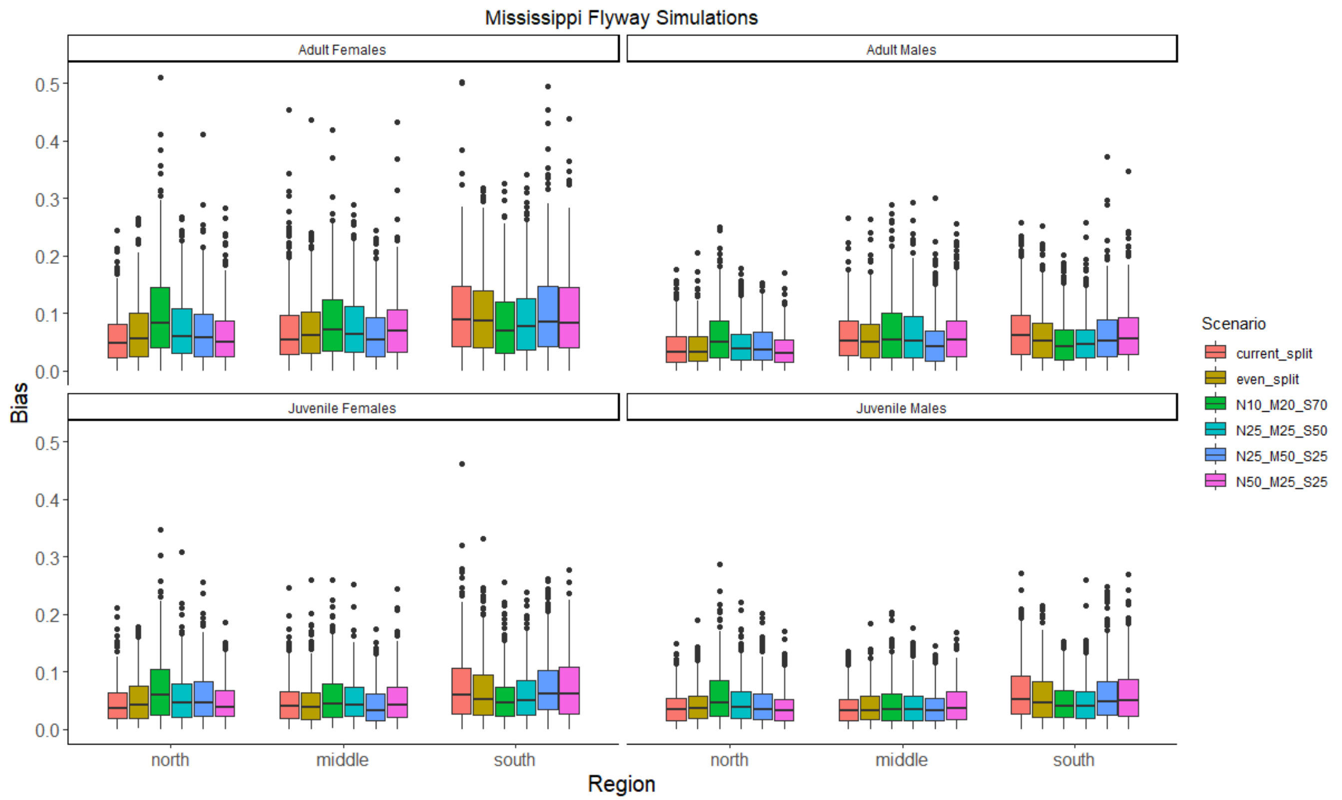

Figure 9. Bias of harvest rate estimates for each Mississippi Flyway Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each region. Bias was derived by simulated each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data.

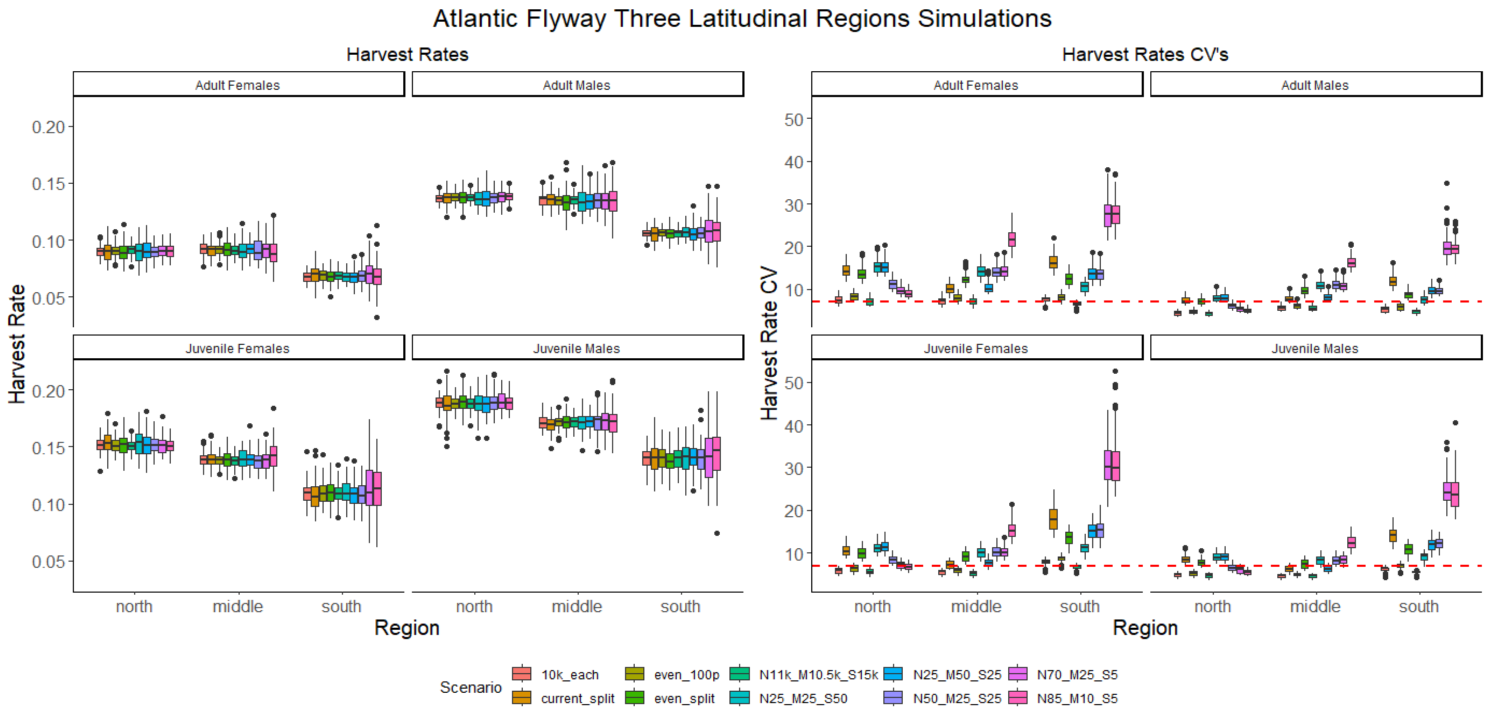

Figure 10. Estimated harvest rates (left) and associated coefficients of variation (CV; right) for each Atlantic Flyway Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each of our identified regions. Red-dashed line depicts the set target of precision for the five-year mean CV at 7%. Estimates were derived by simulating each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance.

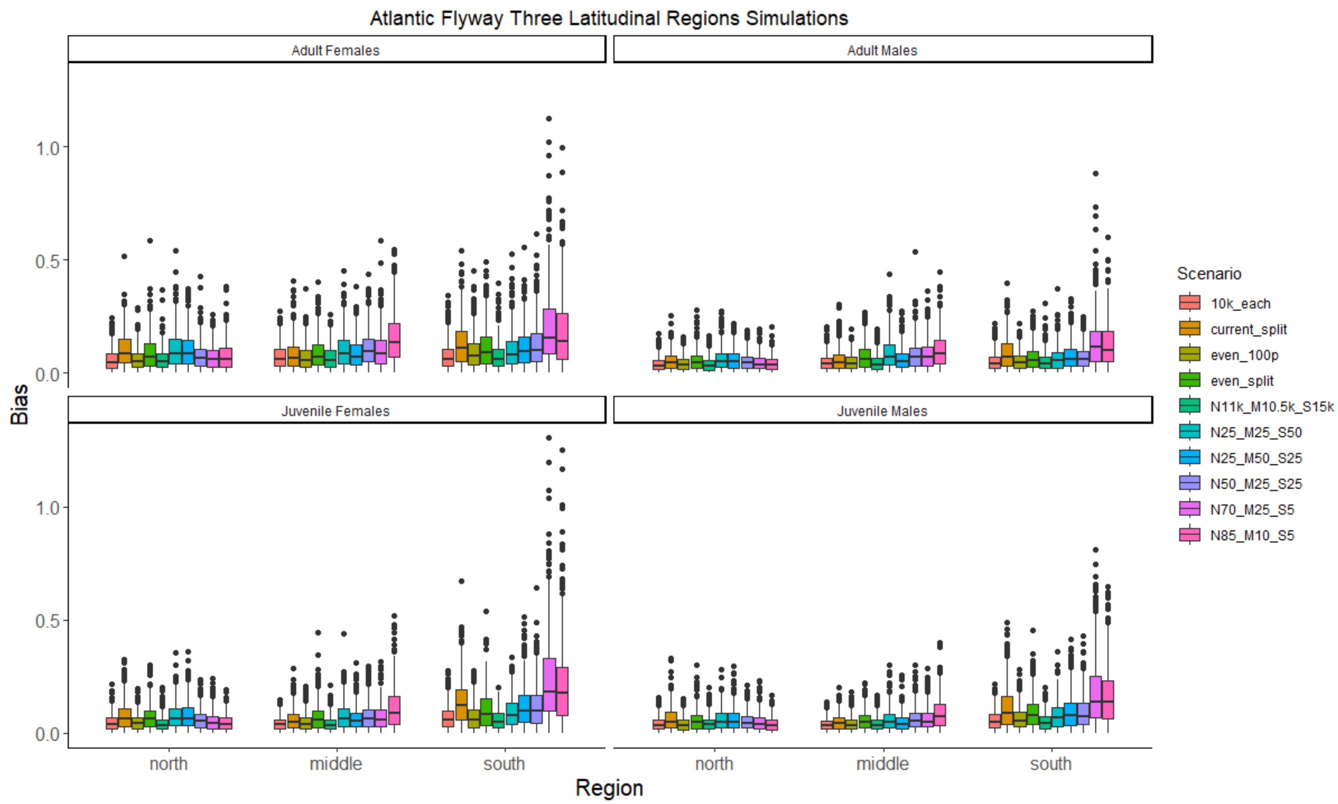

Figure 11. Bias of harvest rate estimates for each Atlantic Flyway Three Latitudinal Region Simulation scenario of each preseason banded wood duck cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male), in each region. Bias was derived by simulated each banding scenario 100 times for a five-year period based on region and cohort specific estimated demographic rates from 2000–2022. Banding frequency for the simulation scenarios was calculated based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. From our estimated harvested rates, we calculated the bias based on the known truth of our simulated data.

APPENDICES

Appendix A. Figures

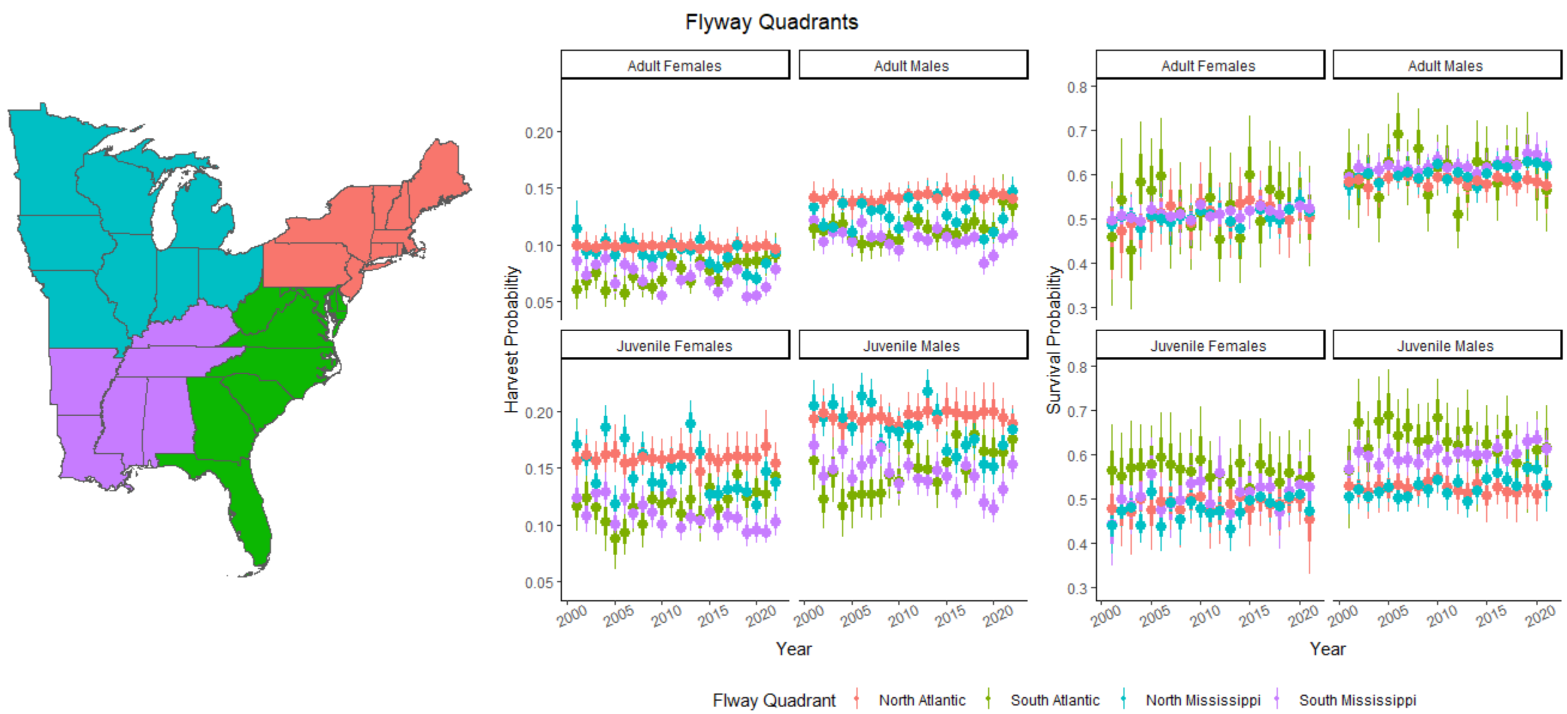

Figure A1. Flyway Quadrants sub-division estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each region shown. These regions were constructed by dividing the U. S. portion s of each Flyway into its northern and southern quadrants by state.

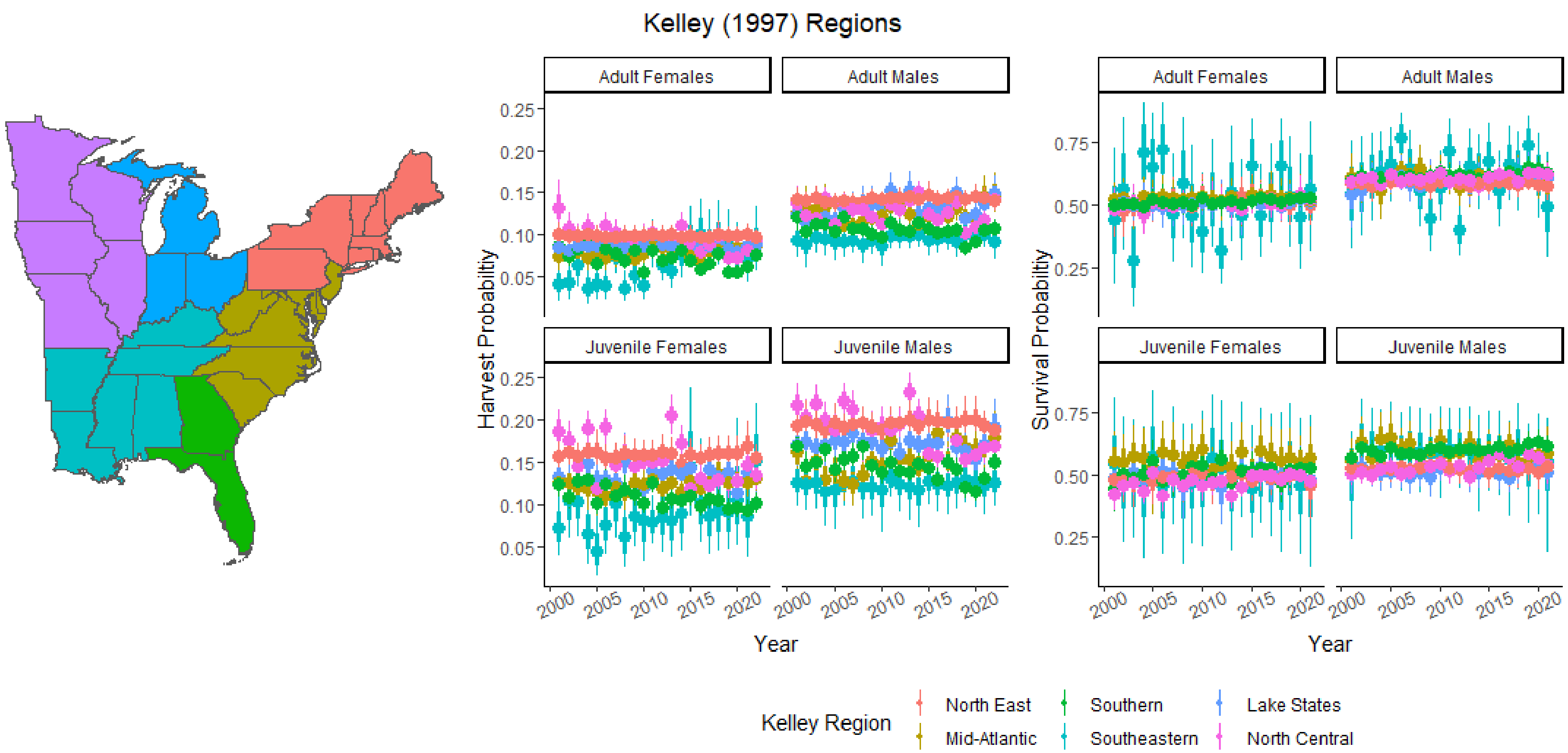

Figure A2. Kelley (1997) Regions sub-division mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each region shown. These are the U. S. portions of the Kelley (1997) regions.

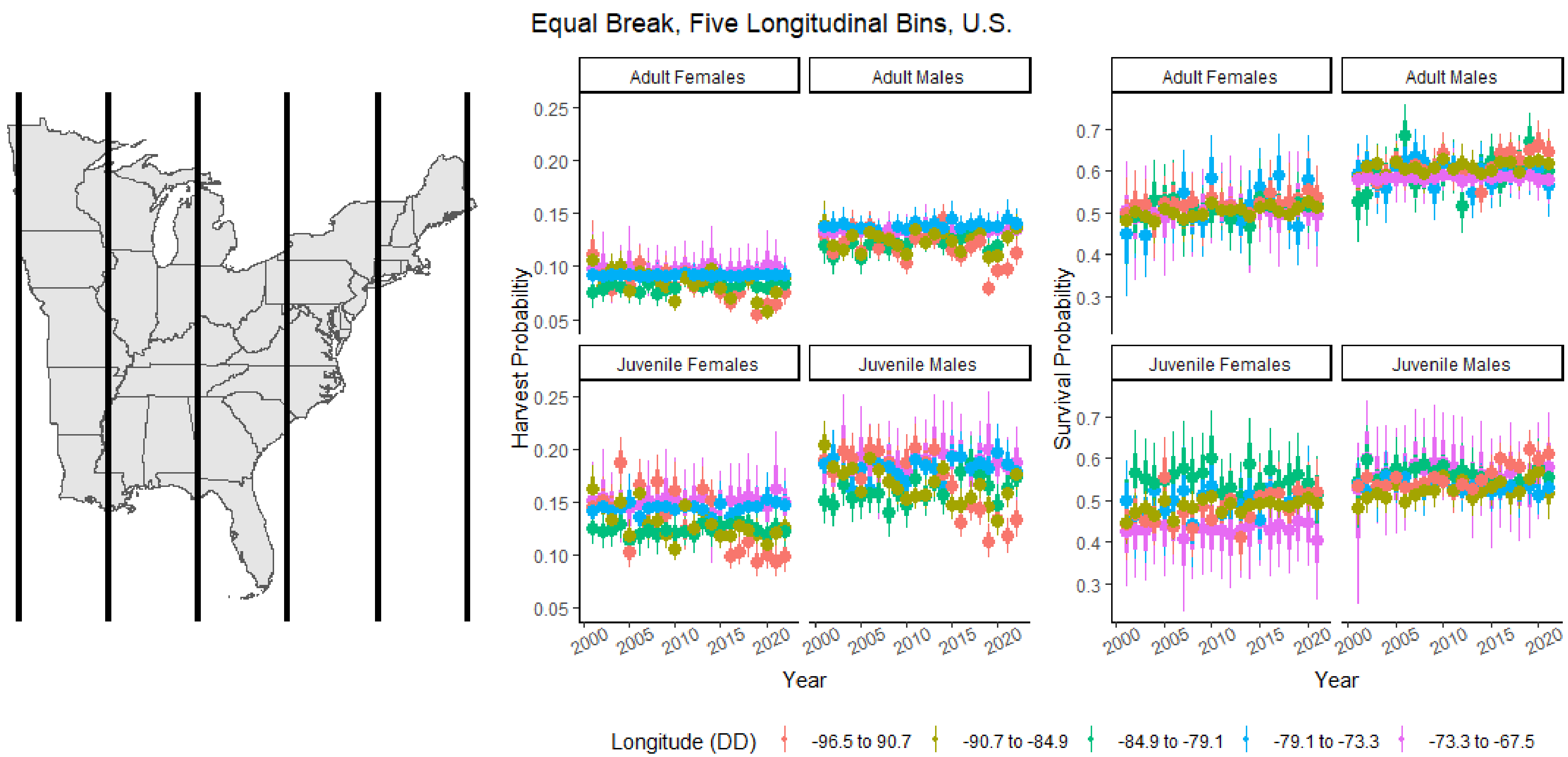

Figure S3. Equal Break, Five Longitudinal Bins, U. S. sub-division estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each bin shown. Bins were created by taking the minimum and maximum longitude that bandings occurred and creating an equal breaks sequence making five-bins of the same distance.

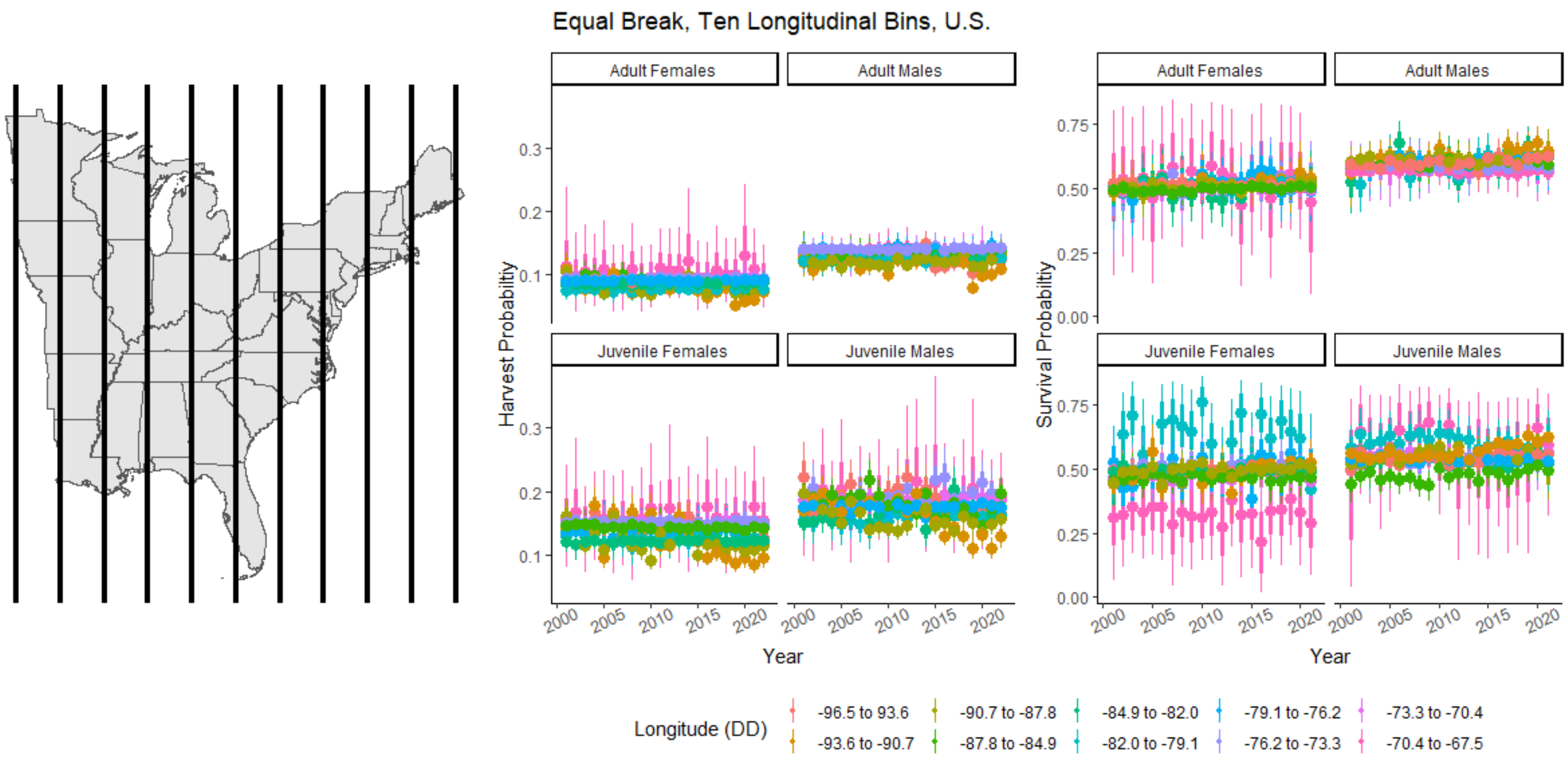

Figure A4. Equal Break, Ten Longitudinal Bin, U. S. sub-division estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each bin shown. Bins were created by taking the minimum and maximum longitude that bandings occurred and creating an equal breaks sequence making ten-bins of the same distance.

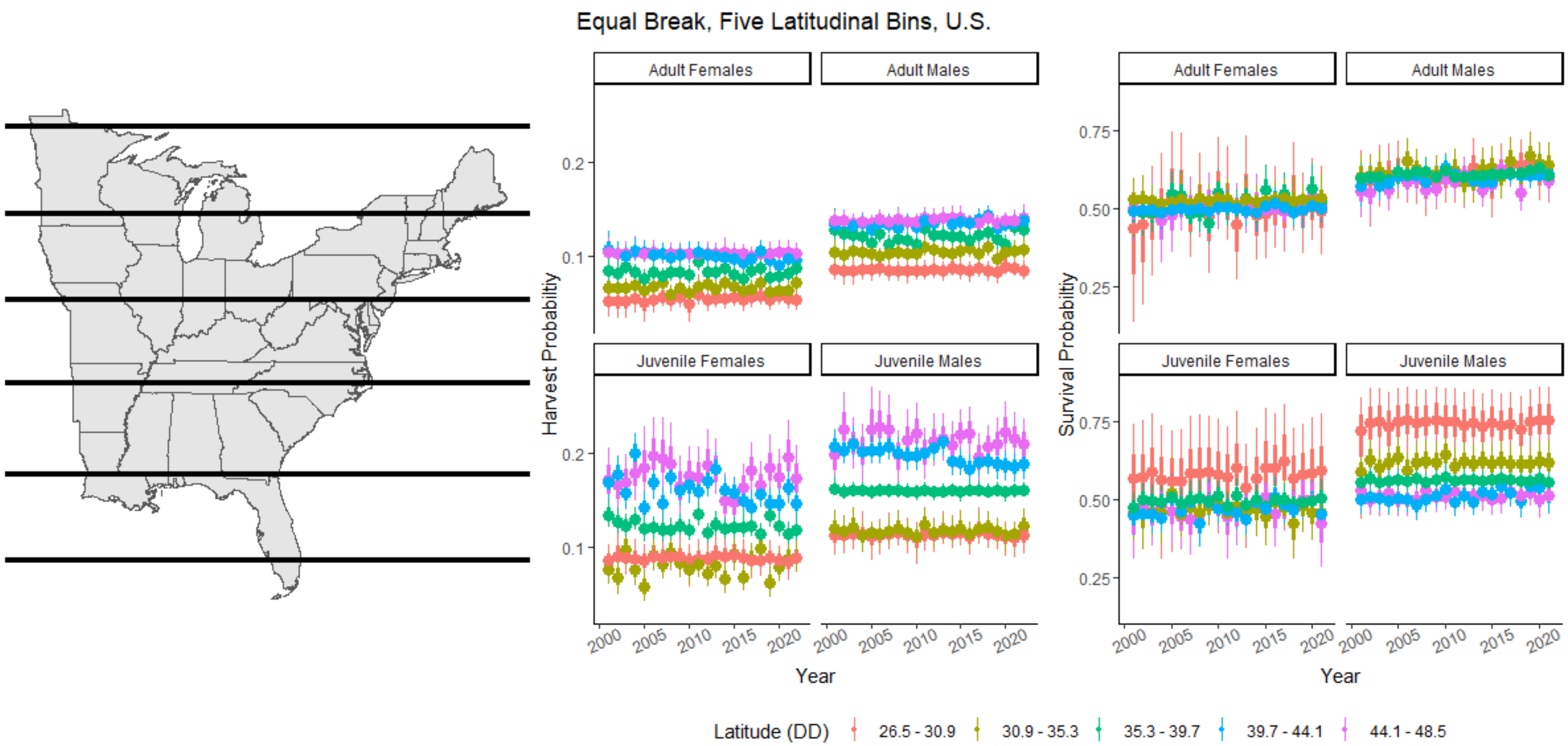

Figure A5. Equal Break, Five Latitudinal Bins, U. S. sub-division estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each bin shown. Bins were created by taking the minimum and maximum latitude that bandings occurred and creating an equal breaks sequence making five-bins of the same distance.

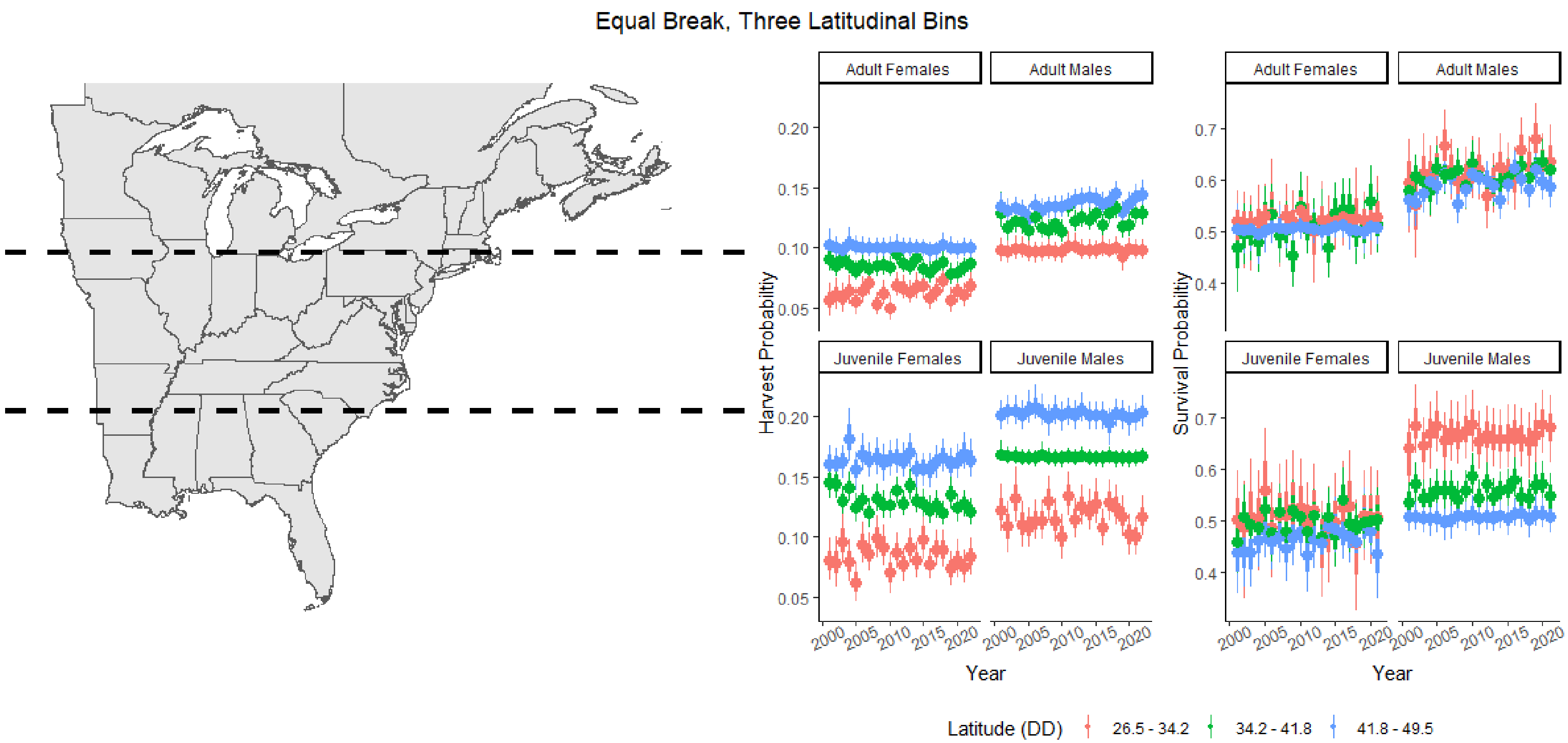

Figure A6. Equal Break, Three Latitudinal Bins sub-division estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each bin shown. Bins were created by taking the minimum and maximum latitude that bandings occurred and creating an equal breaks sequence making three-bins of the same distance.

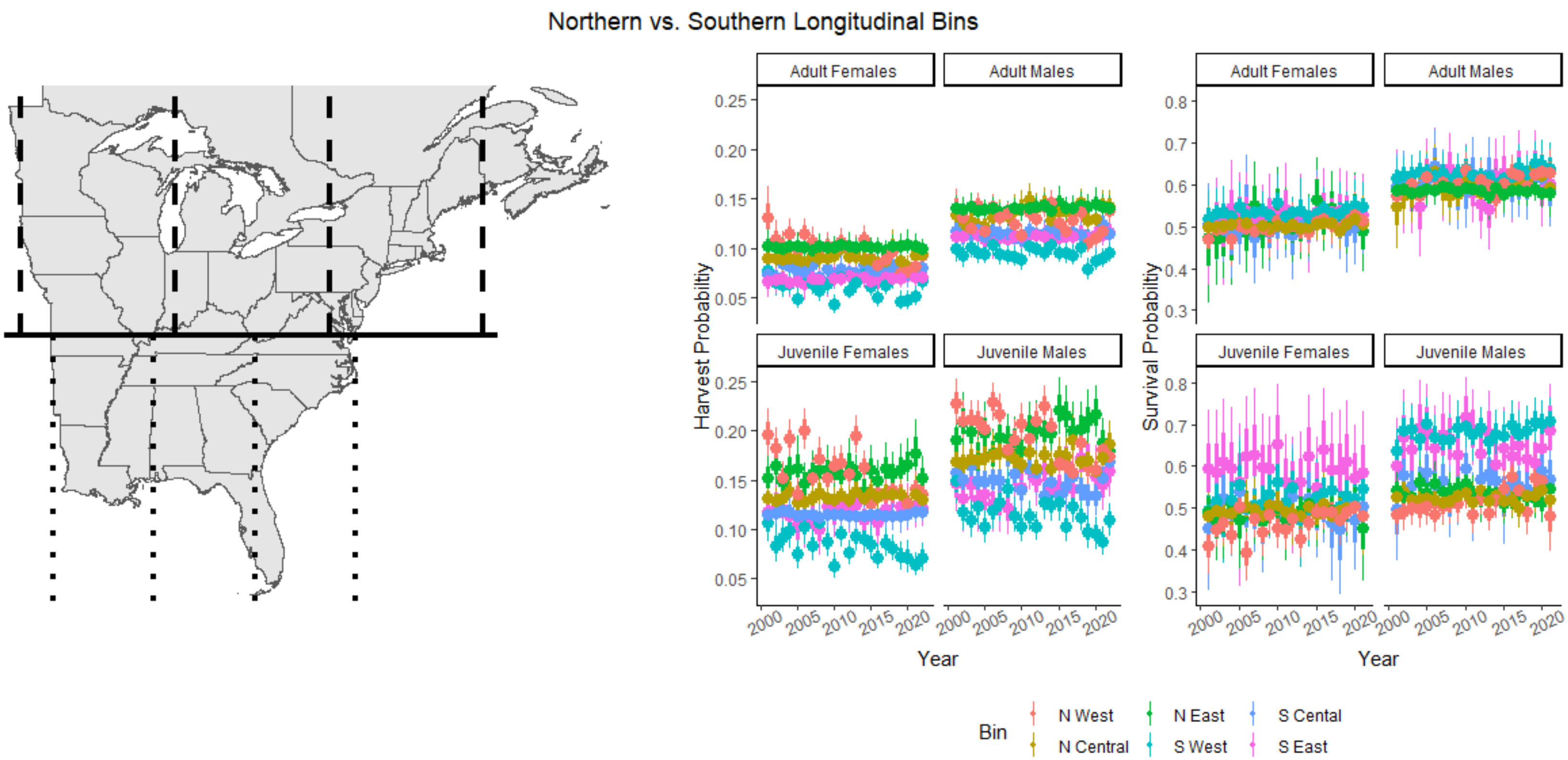

Figure A7. North vs. South Longitudinal Bins sub-division estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each bin shown. Bins were created by divided the eastern North America first into north and south bins based on the min and max latitudinal banding locations. Then created three equal break longitudinal bins separately for the north and south.

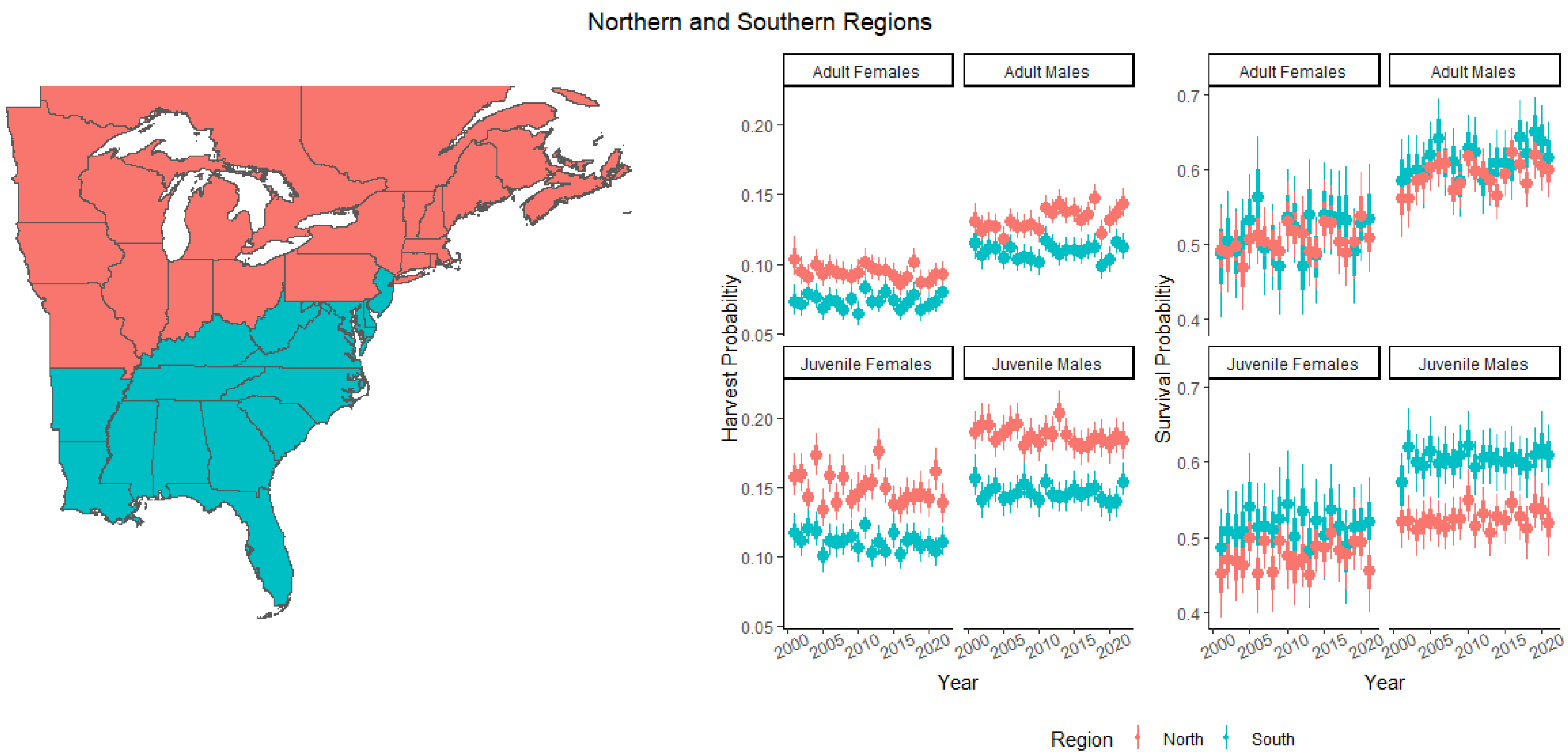

Figure A8. Northern and Southern Regions sub-division estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each region shown. Regions were created by grouping states and provinces based on the northern and southern delineation from Garrettson (2007).

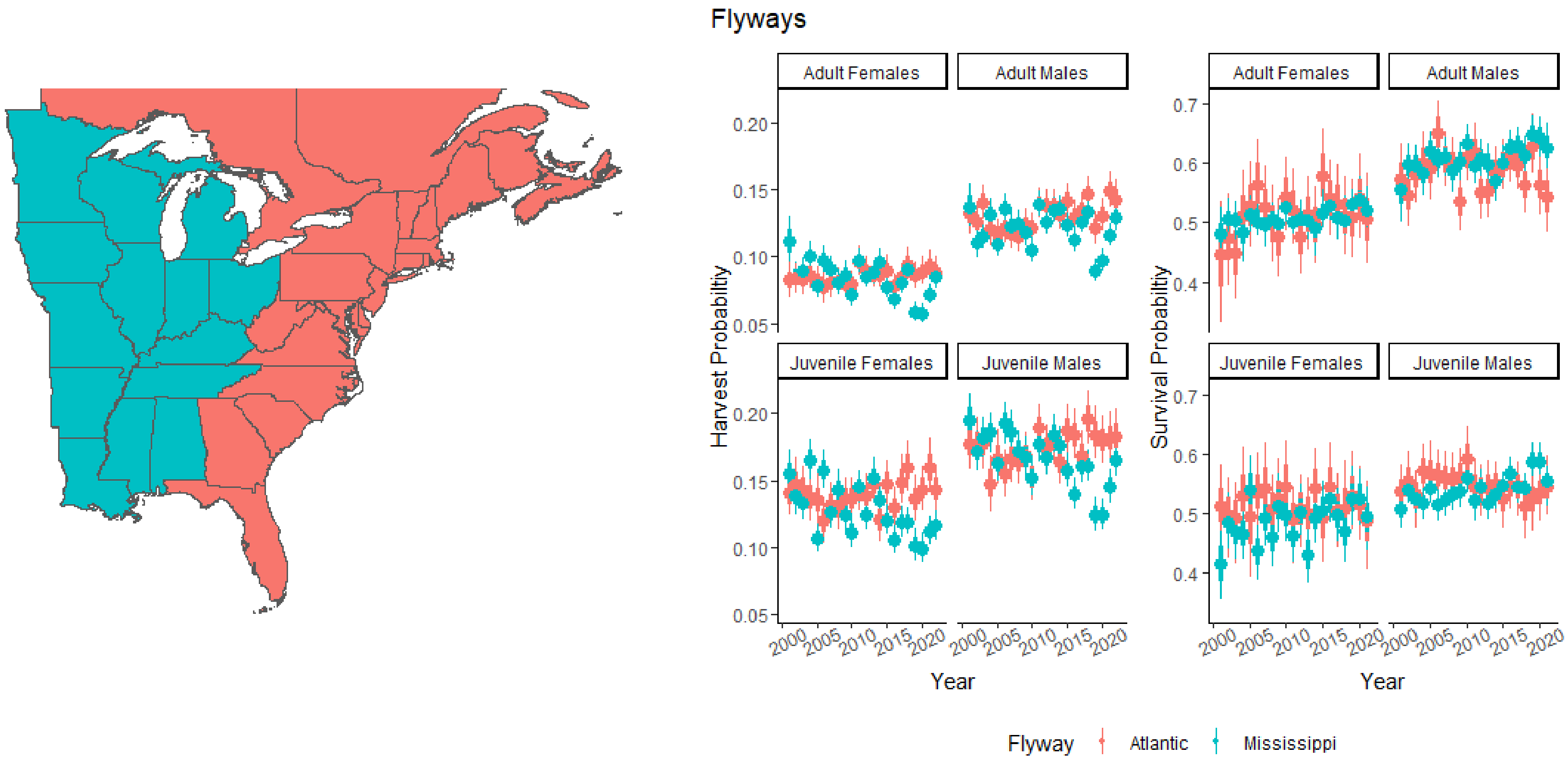

Figure A9. Flyways subdivision estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each region shown. Regions were created by grouping states and provinces based on the Mississippi and Atlantic administrative Flyways.

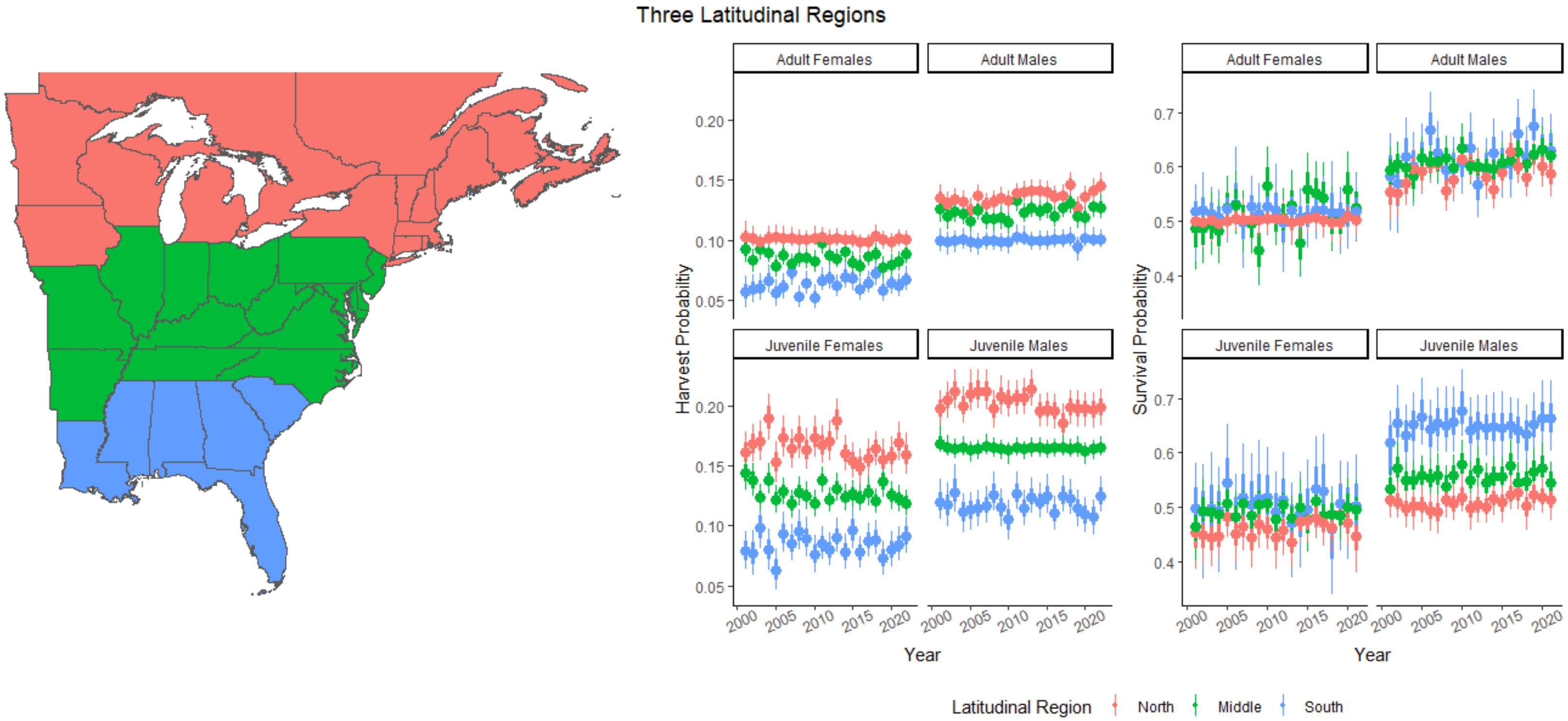

Figure A10. Three Latitudinal Regions sub-division estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in eastern North America from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each region shown. Regions were created by grouping states and provinces based on observed demographic rate variability.

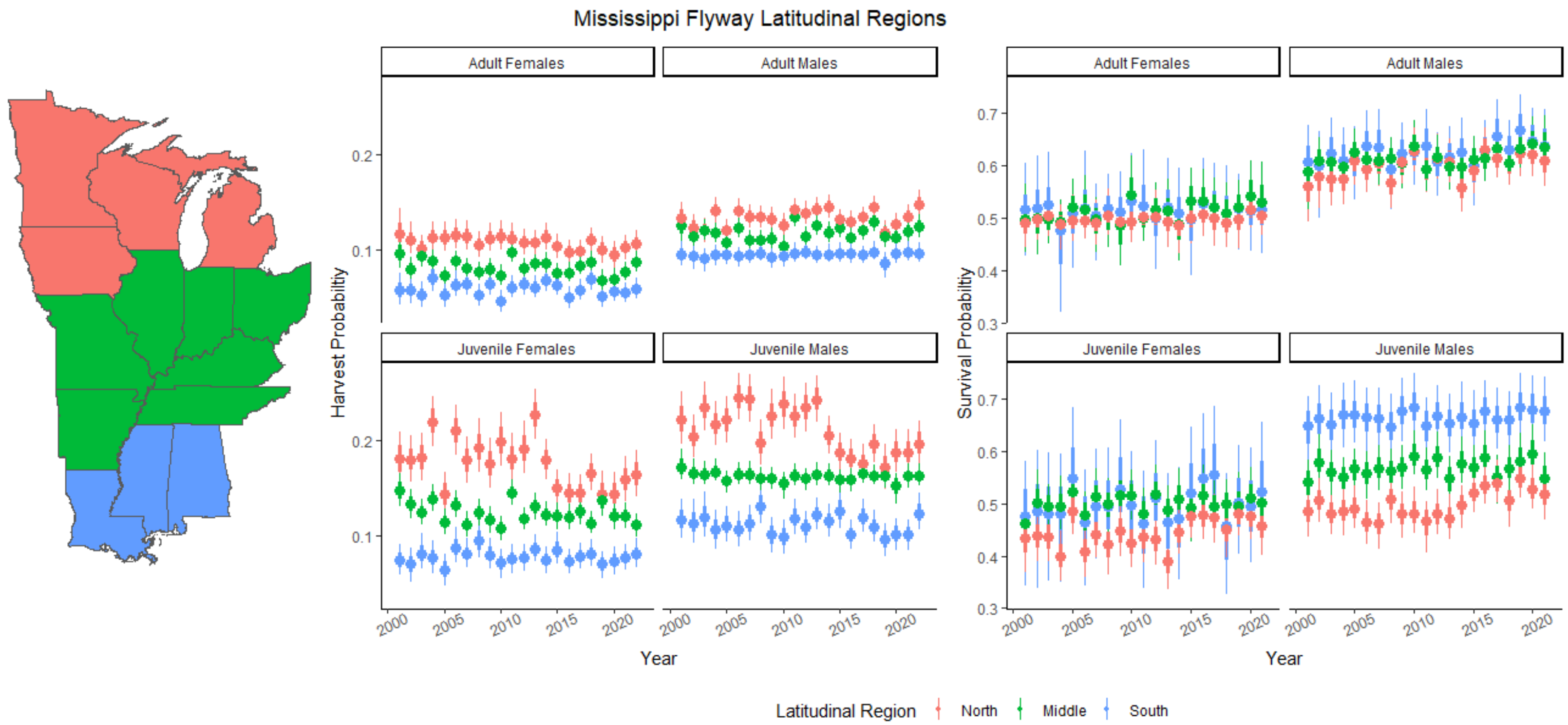

Figure A11. Mississippi Flyway Three Latitudinal Regions sub-division mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in the Mississippi from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each region shown. Regions were created by grouping states of the Mississippi Flyway based on three latitudinal regions determined by demographic rate variability.

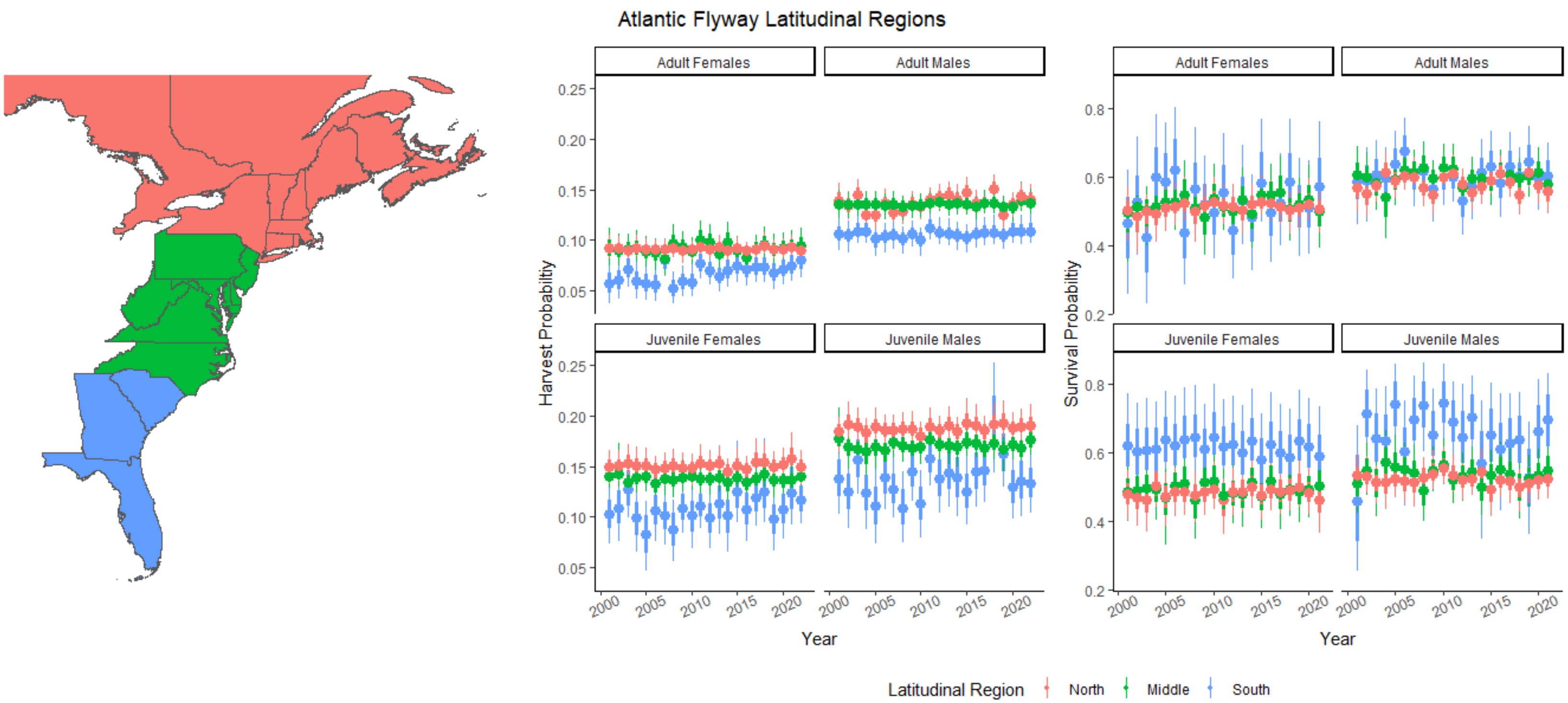

Figure A12. Atlantic Flyway Three Latitudinal Regions sub-division estimated mean harvest (middle) and mean survival (right) probabilities with associated 66% and 95% credible intervals of preseason banded wood ducks in the Atlantic Flyway from 2000–2022. Estimates were derived using a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. We estimated individual demographic rates for each cohort (Adult Female, Adult Male, Juvenile Female, Juvenile Male) in each region shown. Regions were created by grouping states of the Atlantic Flyway based on three latitudinal regions determined by demographic rate variability.

Appendix B. Tables

Table A1. Regional divisions created to asses demographic rate variability of preseason banded wood ducks in eastern North America from 2000–2022 and associated coefficient of variation (CV) ratios. These regions include Mississippi and Atlantic Flyways. CV ratios were calculated using the coefficient of variation within and among the spatial strata.

Regional Division	Adult Female CV Ratio	Adult Male CV Ratio	Juvenile Female CV Ratio	Juvenile Male CV Ratio	Cohort Average CV Ratio
Kelley Regions	2.71	2.81	3.03	2.87	2.86
U.S. Flyway Quadrants	2.63	2.87	2.92	2.99	2.85
Flyways	2.20	2.47	2.41	2.29	2.34
Equal Breaks, Five Longitudinal Bins, U. S.	2.02	2.03	2.17	2.10	2.08
Equal Breaks, Ten Longitudinal Bins, U. S.	2.09	1.73	2.06	1.94	1.95
Equal Breaks, Five Latitudinal Bins. U. S.	3.61	3.92	4.39	5.74	4.41
Equal Breaks, Three Latitudinal Bins, U. S.	3.50	3.52	5.23	6.35	4.65
Three State Latitudinal Regions	3.54	3.45	4.79	5.83	4.40
North vs. South Longitudinal Bins	2.84	2.82	3.25	3.08	3.00
Three Latitudinal Regions	3.75	3.55	4.82	5.96	4.52
Northern and Southern Regions	2.73	3.00	3.49	3.58	3.20
Equal Break, Three Latitudinal Bins	3.81	3.65	4.89	6.96	4.83

Table A2. Banding recommendations to meet the ≤7% five-year mean coefficient of variation target for preseason banded Adult female (AF) and male (AM) wood ducks for our identified Three Latitudinal Regions. Recommendations provided are a total number of deployments given the current percentage each cohort makes of band deployments. Banding are then stepped down to each State and Province using the proportion of National Wetlands Inventory Woody Wetlands (Habitat) in each state for that region weighted by the 2019 Breeding Bird Survey (BBS) Index for that state.

Region	State or Province	BBS Index (2019)	Habitat Area km2	BBS Habitat Weight	BBS Habitat Proportion	AF Region Goal	AF BSS Habitat Goal	AM Region Goal	AM BBS Habitat Goal
North	US-MN	2.018	29,517.80	59,567.00	0.434	10,498	4,551	3,042	1,319
North	US-IA	0.66	1,459.50	963.3	0.007	10,498	74	3,042	21
North	US-WI	1.114	19,817.80	22,077.10	0.161	10,498	1,687	3,042	489
North	US-MI	1.027	23,407.10	24,039.10	0.175	10,498	1,837	3,042	532
North	US-NY	0.498	6,804.10	3,388.50	0.025	10,498	259	3,042	75
North	US-CT	0.714	625.2	446.4	0.003	10,498	34	3,042	10
North	US-RI	NA	219	NA	NA	10,498	NA	3,042	NA
North	US-MA	0.575	1,417.60	815.1	0.006	10,498	62	3,042	18
North	US-NH	0.309	854.1	263.9	0.002	10,498	20	3,042	6
North	US-VT	0.792	747.7	592.2	0.004	10,498	45	3,042	13
North	US-ME	0.093	7,010.90	652	0.005	10,498	50	3,042	14
North	CA-ON	1.253	16,935.00	21,219.60	0.154	10,498	1,621	3,042	470
North	CA-QC	0.143	14,245.00	2,037.00	0.015	10,498	156	3,042	45
North	CA-NB	0.107	5,993.00	641.3	0.005	10,498	49	3,042	14
North	CA-NS	0.145	4,766.00	691.1	0.005	10,498	53	3,042	15
North	CA-PE	NA	NA	NA	NA	10,498	NA	NA	NA
Central	US-NJ	0.238	2,475.10	589.1	0.02	9,912	200	8,519	171
Central	US-PA	0.591	1,315.80	777.6	0.027	9,912	263	8,519	226
Central	US-VA	0.575	3,716.80	2,137.10	0.073	9,912	724	8,519	622
Central	US-WV	0.248	173.6	43.1	0.001	9,912	15	8,519	13
Central	US-MD	0.507	1,672.90	848.1	0.029	9,912	287	8,519	247
Central	US-DE	0.439	613.6	269.4	0.009	9,912	91	8,519	78
Central	US-OH	0.43	1,602.60	689.1	0.024	9,912	233	8,519	201
Central	US-IN	1.005	2,307.80	2,319.30	0.079	9,912	786	8,519	675
Central	US-IL	0.578	3,302.10	1,908.60	0.065	9,912	646	8,519	556

Central	US-MO	0.373	3,091.90	1,153.30	0.039	9,912	391	8,519	336
Central	US-KY	0.467	1,215.20	567.5	0.019	9,912	192	8,519	165
Central	US-TN	0.369	3,163.20	1,167.20	0.04	9,912	395	8,519	340
Central	US-AR	0.571	8,522.60	4,866.40	0.166	9,912	1,648	8,519	1,417
Central	US-NC	0.821	14,529.10	11,928.40	0.408	9,912	4,040	8,519	3,472
South	US-SC	0.286	12,051.00	3,446.60	0.054	11,999	644	6,534	351
South	US-GA	0.711	18,157.40	12,909.90	0.201	11,999	2,413	6,534	1,314
South	US-FL	0.288	26,494.80	7,630.50	0.119	11,999	1,426	6,534	777
South	US-AL	0.386	12,720.70	4,910.20	0.076	11,999	918	6,534	500
South	US-MS	0.835	14,794.30	12,353.20	0.192	11,999	2,309	6,534	1,257
South	US-LA	1.114	20,601.10	22,949.60	0.357	11,999	4,289	6,534	2,336

Table A3. Banding recommendations to meet the ≤7% five-year mean coefficient of variation target for preseason banded Adult female (AF) and male (AM) wood ducks for our identified Mississippi Flyway Latitudinal Regions scale. Recommendations provided are a total number of deployments given the current percentage each cohort makes of band deployments. Banding are then stepped down to each State and Province using the proportion of National Wetlands Inventory Woody Wetlands (Habitat) in each state for that region weighted by the 2019 Breeding Bird Survey (BBS) Index for that state.

Region	State or Province	BBS Index (2019)	Habitat Area km2	BBS Habitat Weight	BBS Habitat Proportion	AF Region Goal	AF BBS Habitat Goal	AM Region Goal	AM BBS Habitat Goal
North	US-MN	2.018	29,518	59,567	0.559	8,993	5,023	3,655	2,042
North	US-IA	0.66	1,460	963	0.009	8,993	81	3,655	33
North	US-WI	1.114	19,818	22,077	0.207	8,993	1,862	3,655	757
North	US-MI	1.027	23,407	24,039	0.225	8,993	2,027	3,655	824
Central	US-OH	0.43	1,603	689	0.054	9,090	494	7,124	387
Central	US-IN	1.005	2,308	2,319	0.183	9,090	1,664	7,124	1,304
Central	US-IL	0.578	3,302	1,909	0.151	9,090	1,369	7,124	1,073
Central	US-MO	0.373	3,092	1,153	0.091	9,090	827	7,124	648
Central	US-KY	0.467	1,215	567	0.045	9,090	407	7,124	319
Central	US-TN	0.369	3,163	1,167	0.092	9,090	837	7,124	656
Central	US-AR	0.571	8,523	4,866	0.384	9,090	3,491	7,124	2,736
South	US-SC	0.286	12,051	3,447	0.144	13,530	1,944	7,829	1,125
South	US-GA	0.711	18,157	12,910	0.538	13,530	7,282	7,829	4,214
South	US-FL	0.288	26,495	7,631	0.318	13,530	4,304	7,829	2,490

Table A4. Banding recommendations to meet the ≤7% five-year mean coefficient of variation target for preseason banded Adult female (AF) and male (AM) wood ducks for our identified Atlantic Flyway Latitudinal Regions scale. Recommendations provided are a total number of deployments given the current percentage each cohort makes of band deployments. Banding are then stepped down to each State and Province using the proportion of National Wetlands Inventory Woody Wetlands (Habitat) in each state for that region weighted by the 2019 Breeding Bird Survey (BBS) Index for that state.

Region	State or Province	BBS Index (2019)	Habitat Area km2	BBS Habitat Weight	BBS Habitat Proportion	AF BSS Habitat Goal	AF State Goal	AM Region Goal	AM BSS Habitat Goal
North	US-NY	0.498	6,804	3,388	0.110	9,449	1,041	3,306	364
North	US-CT	0.714	625	446	0.015	9,449	137	3,306	48
North	US-RI	NA	219	0	0.000	9,449	0	3,306	0
North	US-MA	0.575	1,418	815	0.027	9,449	250	3,306	88
North	US-NH	0.309	854	264	0.009	9,449	81	3,306	28
North	US-VT	0.792	748	592	0.019	9,449	182	3,306	64
North	US-ME	0.093	7,011	652	0.021	9,449	200	3,306	70
North	CA-ON	1.253	16,935	21,220	0.690	9,449	6,521	3,306	2,281
North	CA-QC	0.143	14,245	2,037	0.066	9,449	626	3,306	219
North	CA-NB	0.107	5,993	641	0.021	9,449	197	3,306	69
North	CA-NS	0.145	4,766	691	0.022	9,449	212	3,306	74
North	CA-PE	NA	NA	0	0.000	9,449	0	3,306	0
Central	US-NJ	0.238	2,475	589	0.036	8,475	301	6,397	227
Central	US-PA	0.591	1,316	778	0.047	8,475	397	6,397	300
Central	US-VA	0.575	3,717	2,137	0.129	8,475	1,092	6,397	824
Central	US-WV	0.248	174	43	0.003	8,475	22	6,397	17
Central	US-MD	0.507	1,673	848	0.051	8,475	433	6,397	327
Central	US-DE	0.439	614	269	0.016	8,475	138	6,397	104
Central	US-NC	0.821	14,529	11,928	0.719	8,475	6,093	6,397	4,599
South	US-SC	0.286	12,051	3,447	0.144	9,279	1,333	6,584	946
South	US-GA	0.711	18,157	12,910	0.538	9,279	4,994	6,584	3,544
South	US-FL	0.288	26,495	7,631	0.318	9,279	2,952	6,584	2,095

CHAPTER THREE: SUMMARY AND CONCLUSIONS

Wood ducks hold the peculiar distinction of being one of the most heavily harvested, yet cryptic, waterfowl species in eastern North America. Breeding across a broad geographic range from Canada to the Gulf Coast, wood ducks inhabit forested wetlands that preclude traditional aerial survey techniques. Similarly, ground-based surveys are limited geographically and have low detection probabilities. Subsequently, banding has become the primary source of population monitoring for this secretive duck. Given this constraint, implementing sustainable harvest strategies relies on the quality of monitoring data and analysis derived from preseason banding. However, the utility of banding hinges on key assumptions, including representative sampling and equal survival and recovery rates between distinct subpopulations and migration strategies. Given the species' extensive range and migratory polymorphism, verifying these assumptions remains challenging but critical for unbiased estimation.

The first phase of my study investigated the demographic rate variability of preseason banded wood ducks in eastern North America from 2000–2022. In alignment with previous literature, we found that demographic rates varied along a latitudinal gradient, with higher harvest rates and lower survival rates being estimated for northern banded birds than their southern counterparts. In contrast, I did not find any significant variation of demographic rates along a longitudinal gradient. With these findings I created Three Latitudinal Regions, encompassing the Mississippi and Atlantic Flyways, that maximize harvest rate variability among each region while minimizing the variability within. These new regions identify an appropriate scale to provide new banding goals that not only relieves pressure on individual banding programs, but offers a biologically relevant framework given the species' ecology.

The second phase of my study simulated banding data from the previously estimated demographic rates to investigate how current and shifting banding distributions affect demographic rate estimates and precision. I found that at the Flyway scale, the Mississippi Flyway is meeting precision targets for all cohorts and the Atlantic Flyway is not meeting precision targets for adult females. Simulations at the Three Latitudinal Regions and Three Latitudinal Regions by Flyway allowed me to identify shortcomings in banding deployment and prescribe banding goals to reach precision targets for my identified regions. Our recommended goals are higher for adult females, aiming to rectify their under-representation despite lower recovery rates, though meeting targets will be challenging. Combining Flyway estimates would require less overall banding than independent goals. As shown in our Flyway-level simulations imbalanced banding could still bias Flyway-level rates, underscoring the need for equitable latitudinal sampling.

Our integrated analysis provides guidance for optimizing banding programs to support informed wood duck management. First, delineating regional goals by latitude offers a biologically relevant framework, capturing demographic variation missed by traditional boundaries. However, current distribution shortcomings like declining southeastern sampling could produce biased estimates if unaddressed. Maintaining balanced, representative sampling across breeding latitudes is essential to provide accurate regional and Flyway-level insights. Second, the substantially higher banding goals we recommend for under-represented adult females will increase cohort precision and representativeness. However, coordinated Flyway-level goals can achieve desired precision with fewer total bands deployed. Finally, periodic integrated abundance estimates from banding data are needed to complement existing harvest surveys. Overall, our findings provide a roadmap to harness banding programs through efficient, representative sampling that accounts for subtle demographic variation - ensuring robust mark-recapture data to guide integrated wood duck management